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AN ANALYSIS OF THE RELATIONSHIPS BETWEEN WATER LEVEL FLUCTUATIONS AND CLIMATE, COASTAL LOUISIANA

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ABSTRACT

Water level fluctuations are strongly and consistently related to weather events, and this study demonstrates that a mean regional water level response can be established for each of eight synoptic weather types in coastal Louisiana. The synoptic weather types, used as an index to climatic input, are coupled with numerically filtered water level data, representing meteorologically driven water level changes. Relating the two evaluates the forcing functions of climatic components on complex process-response interactions in coastal environments.

Passages of cold and warm fronts, and the veering of winds from northerly to easterly or southerly as high pressure drifts eastward across the coastal region, causes the strongest, most clearly-defined relationships. Meteorological driving forces weaken as weather types are sustained over the region. Fresh water flooding diminishes the impact of weather types that cause water levels to fall, and augments the effect of weather types that raise water levels.

Reliability of the established relationships is confirmed by a temporal extension of the analysis, demonstrating that the relationships are essentially the same when established with data from any year of a 10-year period. An apparent change in atmospheric circulation, during which the polar jet stream shifted away from the Louisiana coastal region, is evaluated. Total occurrence of meteorologically induced water level fluctuations are thereby shown to be

closely related to the configuration and frequency of change of global atmospheric circulation patterns.

Synoptic climatology offers an avenue for the better understanding of intricate operations of natural systems. This approach may prove useful in establishing a method of accounting for and predicting climatic variability and its impacts on natural processes.

CHAPTER I

INTRODUCTION

Climate is usually defined as the prevailing or average weather conditions in a region over a period of time. Although weather varies from day to day at any location within the region, the individual weather events fit into patterns of regional climate. Consequently physical parameters such as air temperature, relative humidity, cloud cover, radiation, wind, and precipitation possess characteristic means, extremes, and frequencies associated with the region. The climate of a region is, therefore, the regime of expected weather events in that area.

Climate influences environmental features by determining, in large part, the character of the physical environment and influences the processes and responses associated with the natural systems operating within the region. Relationships between climatic elements and water level changes have been recognized for well over 2,000 years, as evidenced by this statement attributed to Theophrastus of Greece: "Receding of the sea indicates a north wind; but its influx a south wind" (Inwards, 1950). That water level changes are important to environmental responses such as biological productivity has also been known for a long time.

Since the elements of climate act as a forcing function for environmental processes, climatological investigations can be designed to study dynamics of natural processes and responses. The coastal wetlands of Louisiana constitute an area of dynamic process-response; fluctuating water levels in the area influence biological productivity in marshes and estuaries because they create circulations that mix fresh and salt water, transport sediments, and export nutrients to adjacent coastal waters. Such circulations, depending upon their velocity, can either promote or inhibit biotic production (Odum and Fanning, 1973).

Although tides periodically flush the coastal wetlands, weather events can augment or diminish the tidal influence as they change the level of the water from which tides rise or fall. Weather events also introduce a frequency of occurrence related solely to climatic variability, and since weather events vary substantially from year to year, month to month, and even day to day, environmental response is affected by this variability. Therefore, identification of the relationships between climate and environmental response might be expected to provide useful insights into the functions of natural systems in the wetlands environments, increasing soundness of management and conservation practices pertinent to valuable natural resources located there.

Defining quantitative relationships between daily water level fluctuations and changing weather in the Louisiana coastal wetlands could provide a measure of the responses of marsh and estuarine waters to the meteorological driving forces which keep these waters in constant motion. Wind direction is especially significant along the Louisiana Gulf Coast because northerly winds drive Gulf waters away from the coast, lowering water levels, and southerly winds drive Gulf waters up against the coastline, raising water levels in bays and estuaries. Drainage from upland streams and local surplus precipitation dilute salinities, change densities, and also affect water levels.

Detailed studies of the effects of these parameters have defined precise physical interactions which result in water level changes. However, such studies have historically been conducted at specific points and along short lengths of the coastline, and there has been no attempt to evaluate these changes within a comprehensive climatic framework or in terms of the entire coastal zone as a region. The results of such a geographical approach could provide a practical and useful evaluation of the regional distribution of weather-induced water level changes along the coast by evaluating responses of water levels to meteorological elements in areas where no climatic data are routinely available. The information obtained could contribute considerably to the body of knowledge that is being amassed about Louisiana's coastal zone, and thus enhance decision-making for economic and management concerns.

The purpose of this research is to identify and measure relationships between the dynamics and variability of climate and daily water level changes in the Louisiana coastal wetlands with the objective of providing a macro-scale evaluation. These objectives can be best fulfilled by organizing the climatic data obtained along the Louisiana coast into a synoptic weather type framework which will enable the data to be related directly to variations in water level responses.

Synoptic weather types account for, and categorize, causal parameters such as wind speed and direction, precipitation, evapotranspiration, and fresh water surplus, providing a comprehensive index to assess the contribution of climate's components in forcing water level fluctuations.

The scope of this research includes the entire length of the Louisiana coastline and includes water level data measured in rivers, bays, estuaries and other locations which may represent the diverse environments of the Louisiana coastal wetlands (Fig. 1.1). The waters that circulate in these areas create conditions for biological productivity that are unmatched anywhere else in the contiguous United States (Murray, 1976). Michael (1916) was one of the first to acknowledge that details of typical, average, and extreme physical conditions are needed for understanding relations between coastal biota and their environment. Water level fluctuations provide an "energy subsidy," reducing the metabolic cost of counteracting physical stress and enhancing the productivity of these tidal environments (Odum and Fanning, 1973). Smith (1974) concludes that the "relative importance of meteorological forces along the coast necessitates their inclusion" in a study of tidal environments.

A fundamental concern of geographic research is the proper understanding of the physical environment and aspects of the complex process-response interactions that shape it. This investigation has as its goal the contribution of knowledge about the role weather plays in providing energy for water level fluctuations. A review of other

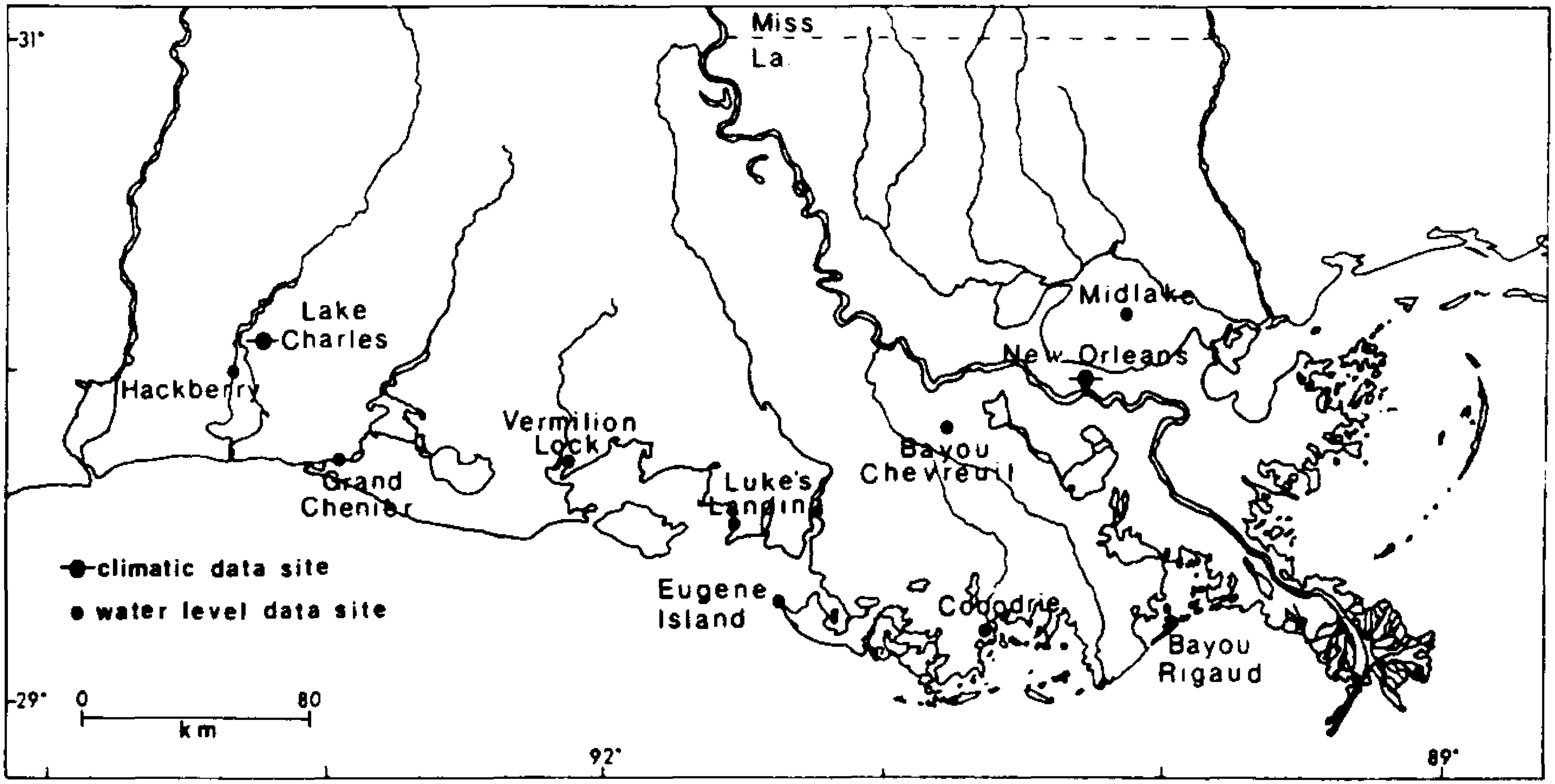

Figure 1.1: Location Map, Louisiana Coastal Area

investigations of water level response to climatic input emphasizes the value of the perspective of this investigation. Since this is the first investigation into relationships on a regional scale, the review also helps to focus the direction of this research. Selected examples of these investigations and some pertinent results are reviewed in the next chapter.

CHAPTER II

PREVIOUS INVESTIGATIONS AND PRESENT STATE OF KNOWLEDGE

Introduction

The purpose of this chapter is to examine the history of the search for relationships between water level changes and meteorological events and to summarize the current state of knowledge on the subject. Previous investigators have usually approached the problem from two perspectives:

1) hydrodynamic responses with applications to engineering problems or basic scientific inquiry, and

2) ecological consequences of water level dynamics.

Both broad categories embody studies of open ocean waters; intermediate estuaries, bays, and near-shore coastal waters; and inland lakes and reservoirs.

Hydrodynamic Response Category

Almost all the studies in the hydrodynamic response category treat weather as a source of energy acting upon water levels, and consider wind and barometric pressure as the most important parameters. The majority of the studies deal exclusively with wind as a forcing function and attempt to develop equations and models to explain and predict wave and water level set-up as a response to wind shear stress on the surface of the water at specific locations and times.

Open Ocean Waters:

Water level changes caused by weather events in the open ocean have been extensively explored in the hydrodynamic category. These types of investigations have dealt rigorously with wind set-up and surge due mainly to storm action. Pertinent equations and derivations are found in the works of Ippen (1966) and Bodine (1971).

Estuarine, Bay, and Near-Shore Waters:

Levikov and Prival'skiy (1972) developed a linear hydrodynamic model which related the spectrum of non-regular sea level variations to the spectra of atmospheric pressure and wind stress. Their theoretical approximations of near-shore water level response functions compared favorably with water level data obtained directly from the Barents Sea. Reid and Bodine (1968) used numerical techniques to develop a hydrodynamic model for meteorologically induced changes in water levels of Galveston Bay. Murray (1972) showed how intense winds associated with specific sectors of high and low pressure cells dominate three-dimensional circulation along the eastern Louisiana coast. Kjerfve (1975) related surface slope vectors and water level dynamics in a bay to tidal waves and wind stress in fair weather conditions. He made several successful predictions of water surface slope under varying wind and pressure conditions.

Lakes and Reservoirs:

One study of enclosed water bodies, that of Saville, et al (1962), provided a widely used equation to predict wind set-up in lakes and reservoirs. They defined wind set-up as the tilting of the water surface caused by movement of the surface water toward the lee shore as a result of tangential stress between wind and water and the piling up of water against the windward shore. Consequent hydrostatic unbalance results in a return flow at some depth, and the resulting surface slope is that necessary to sustain the return flow under conditions of bottom roughness and cross-sectional area of flow which exist. The equation, modified from original equations developed by Dutch engineers on the Zuider Zee, takes the form

$$Z_s = \frac{V_w^2 F}{1400d}$$

where Z_s = rise above still water level, in feet

V_w = wind speed in mph

F = fetch, in miles

d = average depth of water body, in feet.

Thus change in water level is proportional to the square of the windspeed, and is generally larger in shallow basins with rough bottoms.

It is apparent that when data on the surrounding configuration of the shoreline, fetch across open water, and wind speed are available for a particular location and time, equations are available to estimate water level response at that point with reasonable accuracy. However, these equations are limited to engineering applications relative to necessary height and strength of levees and retaining structures for particular storm events. They were developed for application at a particular location and for a particular time period and therefore they are not practical for a general analysis of environmental consequences of normal water level changes along the coastline of an entire region on a day-to-day basis.

Analyses of Measured Water Level:

Such rigorous analyses as those described above represent a theoretical approach to establishing the relationships sought by predicting the water level response to hydrodynamic parameters. A different approach uses the measured water level data and focuses on the interpretation of actual water level changes (Languet-Higgins and Stewart, 1963; Groen and Graves, 1963). This type of approach, though less rigorous than the former, complements the theoretical-predictive approach.

Miller (1958) numerically filtered tidal and higher frequency variations from observed water levels, termed the residue "non-tidal sea level," and empirically ascertained the effect of winter storms on open coast water levels in New England. He did not attempt to develop mathematical relations between the variables, and he did not verify his results with predictions that could be checked.

Alvarez (1970), working with water levels at the mouth of Blanca Bay, Argentina, classified cases in which water level showed positive, negative, and null anomalies from predicted astronomic tide water levels and analyzed relationships between the anomalies and the most significant parameters. He determined the meteorological situations causing the major positive and negative effects and found that delays between wind action and water response varied from zero to five hours.

Chevre (1971) investigated the factors that influenced the water level of a lagoon in the Tuamotu Archipelago and outlined the synoptic meteorologic situation which resulted in sudden anomalous rises in water level.

Ecological Consequence Category

Investigations in the ecologic consequence category have focused upon the importance of fresh and salt water exchange in determining the character of the environment in tidal estuaries. From this perspective, weather has been related mainly to three-dimensional circulation of these waters, with particular reference to the effects of winds and river runoff.

Wind:

Collier and Hedgepeth (1950) attributed the most noticeable changes in bay water level along parts of the Texas coast to wind effects having recognized that flats and marshes available to young marine organisms are determined, both in area and time, by the regime of water levels. They cited the Tide Tables for 1949 in which this advice was given: "Inside the bays the periodic tides are negligible, the variation in water level depending principally upon the wind." Even though Collier and Hedgepeth recognized that wind effects could disrupt tidal predictions, they suggested that the effect of wind was more correctly evaluated if considered as a disturbance of the primary tidal forces which govern water level fluctuations. Their results showed that north winds set up a diphasic swing (seiche) in water levels when their impact was abrupt and forceful, or a continued depression of water levels if sustained, and they also indicated a strong causal relationship between these wind effects and salinity exchanges.

Copeland, et al (1968) assessed the ecologic importance of water levels in shallow bays and estuaries of the Texas coast. They noted that slight fluctuations in water level flooded or drained thousands of acres of mud and grass flats, setting up cycling of nutrients. They observed that a tremendous influence on relative water levels was exerted by the wind, and that, in fact, water level was regulated by wind direction, intensity, and duration. Ketchum (1951) stated that the distribution and exchange of salinity, extreme conditions, planktonic populations, and estuary-spawned eggs were related regularly to tidal oscillations, in a longer term to river run-off, and more erratically to effects of wind.

Chabreck (1972) stated that changing weather conditions along the Louisiana coast altered the level of water from which tides periodically rose and fell, thereby altering the time of occurrence and levels of high and low tides. He found that southerly winds piled Gulf water up along the coast, then, if prolonged, moved it inland inundating marshes to a depth determined by the duration and velocity of the wind. He reported that northerly winds had the opposite effects on coastal water levels, that tides two feet below normal which left marshes practically dry were not uncommon.

River Runoff:

Both precipitation and river runoff have been shown to reduce salinity and density by adding fresh water to the coastal zone. Meade and Emory (1971) asserted that density and volume variations related to river discharge into coastal waters accounted for 21% of the water level variation along the Gulf Coast. Their hypothesis was that low density water occupied more volume to constitute a given mass and thus water level stood higher in areas or times of large river discharge.

Other investigators have approached the relationships between runoff and water levels from different perspectives. Gunter (1967) reported that local heavy rainfall and the ensuing runoff raised water levels in back bays and other coastal areas that drain slowly, but disturbance to tides was slight and only temporary. Gunter and Shell (1958) noted that water resource projects which regulate runoff into the coastal area tend to stabilize fluctuations in water levels. They also related wet and dry years to the corresponding state of the marsh and its productivity.

Utilization of Synoptic Climatology

The preceding review of prior investigations into the relationship between meteorological events and water level fluctuations has shown that several methods of analysis have been employed to achieve a broad spectrum of objectives. In some of the analyses the synoptic meteorological situation has been found to indirectly influence specific water level changes. However, a literature search has not revealed any systematic analysis which relates atmospheric circulation and recurrent weather conditions at a particular geographic location to a repetitious (and possibly predictable) response of water levels. Furthermore, most of the investigations reviewed were local in scope, and macro-scale relationships have not been established for the totality of weather in any region.

A repeated theme in the literature has been the idea of relating atmospheric circulation and resultant weather conditions to environmental response. Such a direction in climatology was foreseen and adopted by Thornthwaite (1953, 1961), Miller (1957, 1965), and Tweedie (1967), all of whom emphasized a need for more interpretation of the relationships between climate and environmental responses. Hare (1966) recognized the ecological, physiological, and hydrological forms of environmental climatology. Dzerdzeevski (1968) devised a circulation classification scheme which has as one objective the providing of a basis for identifying relationships between the dynamics of climate and the dynamics of natural processes. Barry and Perry (1973) published a textbook in which they present applications for, and usefulness of, a synoptic climatology framework in environmental studies.

It is clear that synoptic climatology has not been used to determine substantive relationships between water level fluctuations and climate of a region. Moreover, existing theories and equations appear to be useful only when applied to a particular location and time or only when certain data are available.

Synoptic climatic analysis offers several advantages if the objective is to identify comprehensive relationships on a regional scale. For instance, investigating water level fluctuations associated with a single type of weather every time that type of weather occurs may promote clearer understanding of the interactions. Additionally, size of the sample is dependent only upon the time frame chosen by the investigator. If an observed water level fluctuation can be related to a certain synoptic weather situation, and if that fluctuation is assumed to be caused by the occurrence of that type of weather, measurement of water level responses when that particular weather recurs meaningfully identifies the water level response associated with that synoptic weather pattern. Expected response and variation in response can thus be determined for given weather circumstances, and relationships between the two can be established.

Muller (1977) has developed a synoptic climatic scheme which can be used to study these relationships. The next chapter explains how this scheme has been modified and applied to attain this particular objective.

CHAPTER III

METHODS AND PROCEDURES

Introduction

A synoptic climatic scheme places all observed weather in a region into designated types. Based upon this classification, the responses of water levels to the entire spectrum of weather events in the area can be estimated. The way in which a synoptic climatic scheme for the Gulf Coast of Louisiana can be developed for this purpose is divided into three major stages:

1) reduction of climatic data into a calendar of synoptic weather types and assessment of their associated properties;

2) reduction of water level data to a residual component representing the meteorologically driven fluctuations; and

3) development of correlation methods.

Climatic Data

Source and Condition:

Almost no meteorological or climatological data are observed along the Louisiana coastline and assessment of environmental responses to climate in that area is consequently difficult. Meteorological and climatological data are taken at first-order stations of the National Weather Service at Lake Charles and New Orleans, however, both of which are near the coast. These data can be reorganized to form a baseline for the synoptic climatic analyses employed in this research. Additionally, daily precipitation and temperature data observed at cooperative stations of the National Weather Service located within the coastal zone, although neither as standardized nor as homogeneous as those recorded at the first-order stations, are nonetheless employed in water budget computations.

Because both of the first-order stations are at airport locations, site factors are relatively similar. Observations are taken on an hourly basis by professionals using standardized sensors and methods. These data represent the best and most homogeneous climatic records available in the coastal zone and are published in a variety of forms by the Environmental Data Service of the National Oceanic and Atmospheric Administration.

Reduction:

The observational first-order data have been reorganized into a synoptic climatology framework to provide an environmental climatic baseline useful for evaluation of climate and process interactions within the coastal zone (Muller, 1977; Muller and Wax, in press; Borengasser, et al, in press). Muller (1977) originated the synoptic scheme, determining eight synoptic weather types and assessing the properties of each one. The following descriptions of his methodology and of the eight synoptic weather types are summarized from his work with the New Orleans climatic data.

The daily weather map of the National Weather Service is utilized to classify the weather at Lake Charles and New Orleans at 0600 CST into eight all-inclusive types. These synoptic types are Pacific

High (PH), Continental High (CH), Frontal Overrunning (FOR), Coastal Return (CR), Gulf Return (GR), Frontal Gulf Return (FGR), Gulf Tropical Disturbance (GTD), and Gulf High (GH). Each synoptic type, representative of a causal atmospheric circulation, is illustrated (Fig. 3.1) and described briefly below.

Pacific High (PH): The circulation usually brings mild and relatively dry air following a cold front across southern Louisiana. Most often the center of the surface high is over the eastern Pacific Ocean or west of the Rocky Mountains.

Continental High (CH): The center of the anticyclone is usually east of the Rocky Mountains, and the associated surface air flow is from Canadian or Arctic regions. This weather type is restricted to fair weather associated with the core of the anticyclone.

Frontal Overrunning (FOR): This synoptic type occurs frequently when the polar front is more or less stationary along the Gulf Coast or over the northern Gulf. Frequently waves develop along the front over the western Gulf, and then sweep northeastward bringing heavy clouds and precipitation to southern Louisiana. Generally either polar or Arctic air is associated with this weather type.

Coastal Return (CR): When the crest of an anticyclonic ridge drifts to the east of Louisiana, surface winds over New Orleans veer from northeast to east to southeast. During winter and spring the surface air usually represents continental polar air modified by short passages over the Atlantic and Gulf during clockwise circulation near the Gulf Coast. During summer and autumn, in contrast,

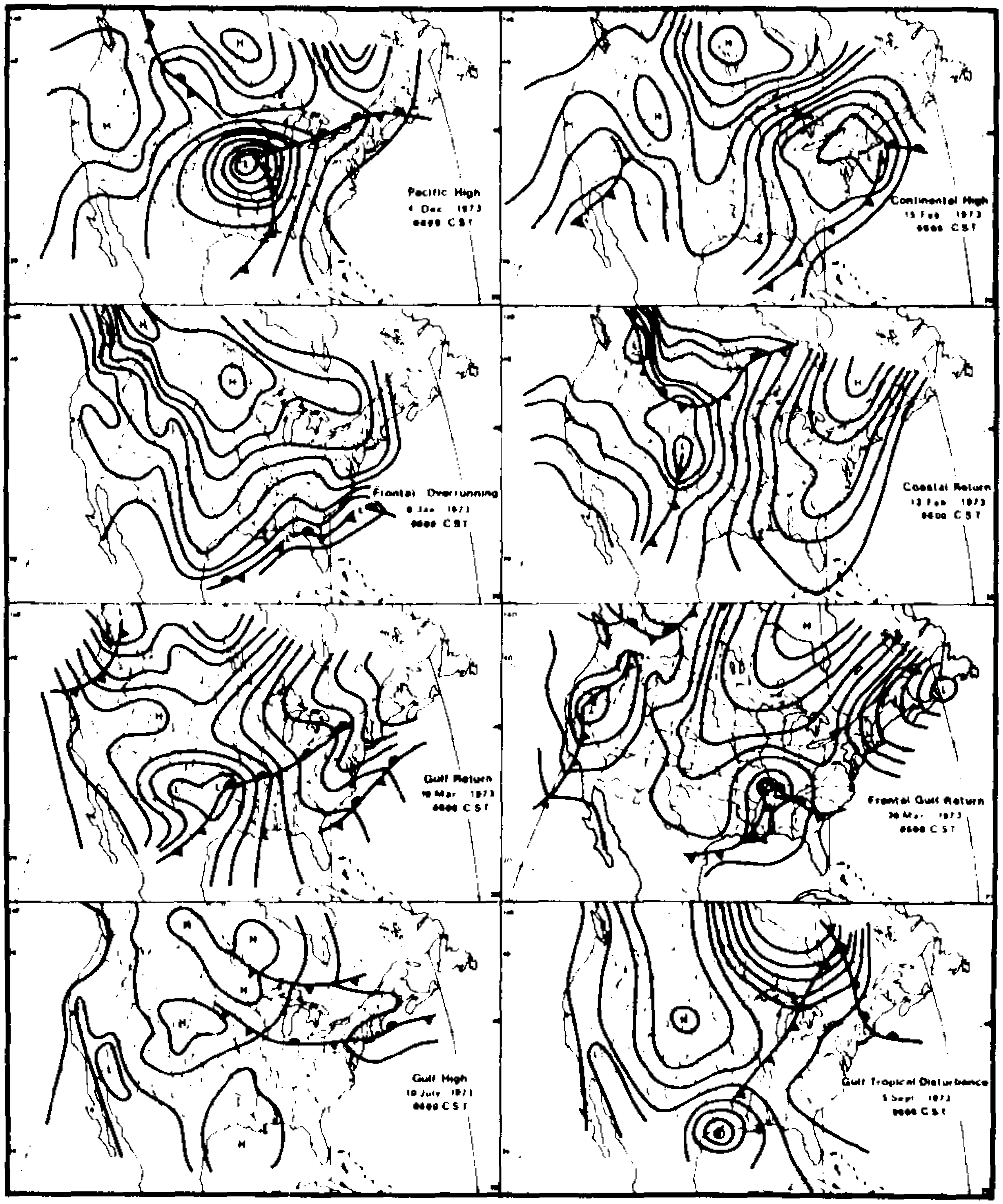

Figure 3.1: Illustrations of Synoptic Weather Types (modified from Muller, 1977)

this type also includes the Bermuda High situation, when a ridge of tropical air extends westward from the Atlantic over the southeastern states, and the air flow over New Orleans is again from easterly components.

Gulf Return (GR): When the anticyclonic ridge drifts further eastward, the isobar configuration usually results in a strong return flow of maritime tropical air from the Caribbean and Gulf on the western margin of the ridge. A similar flow occurs when developing low pressure over the Texas panhandle begins to sweep northeastward. In both of these situations, the coastal return flow of modified continental air is gradually replaced by moist tropical air as surface winds continue to veer from east to southeast to south.

Frontal Gulf Return (FGR): When the return flow is affected by convergence or lifting along an approaching front, the resultant weather deserves special designation as a separate weather type. Arbitrarily, this type includes periods when a cold front from the west or north is located within a zone extending out about 300 miles from New Orleans or Lake Charles. This type also includes periods after a northeastward-moving warm front has crossed over New Orleans or Lake Charles, but only until the front has progressed about 100 miles to the northeast. Hence, FGR is restricted to warm-sector periods when fronts are affecting the weather over either of the two stations, and GR includes the same air flow with distant fronts.

Gulf Tropical Disturbance (GTD): During summer and fall, southern Louisiana is occasionally influenced by tropical systems which usually drift from east to west across the northern Gulf. These disturbances range from relatively weak easterly waves to rare but severe hurricanes such as Camille in 1969. The tropical disturbances are associated with instability through deep moist layers, and copious precipitation is often produced.

Gulf High (GH): Especially during summer there are periods when the western extension of the Bermuda High is displaced southward over the Gulf of Mexico, and the weak local circulation is from the southwest. This flow consists usually of maritime tropical (mT) air, but occasionally somewhat drier continental tropical (cT) air from western Texas will reach the Louisiana coast. Very occasionally during winter and spring a flat high pressure cell over the Gulf will also draw warm, dry air over Louisiana from Texas or Mexico.

At both Lake Charles and New Orleans each month is then organized into a weather type calendar. Although weather is a continuum, the time of initiation, duration, and time of termination of each of the weather types is fixed by consulting the data published in a three-hourly format in the Local Climatological Data for each location. Table 3.1 illustrates a portion of the synoptic weather type calendar for Moisant Airport, New Orleans, during January 1973 showing the occurrence of the synoptic weather types and the passage of warm and cold fronts. For example, the month opened with the FOR type persisting for 54 hours until a warm front passage at 0600 on January 3. The warm front initiated the FGR type which persisted for only six hours when the PH type followed a cold front passage. The PH type

Table 3.1

Synoptic Weather Type Calendar
New Orleans, Louisiana
January 1-20, 1973

Type	Date	Hour	Hours Duration
Frontal Overrunning	1	0000	54
warm-front passage	3	0600	
Frontal Gulf Return			6
cold-front passage	3	1200	
Pacific High			24
cold-front passage	4	1200	
Frontal Overrunning			21
warm-front passage	5	0900	
Frontal Gulf Return			21
cold-front passage	6	0600	
Frontal Overrunning			150
Continental High	12	1200	93
Coastal Return	16	0900	27

(from Muller, 1977)

terminated 24 hours later when another cold front at 1200 on January 4 initiated the FOR type.

The calendars and summaries of climatological properties of each synoptic weather type, constructed with data from the National Weather Service first-order stations, provide climatic baselines from which inferences about environmental interactions may be drawn. For instance, wind is assumed to be the dominant element forcing meteorologically induced water level changes, but wind data available to use in organizing periods of similar wind conditions along the entire coast are too sparse to be effectively employed for a single element analysis that would fulfill the objectives of this research. Coast Guard stations make observations at a few points along the coast, but the data are usually not published by the National Weather Service. Private industries keep some records, but they lack homogeneity, and furthermore they are not routinely available for inspection or use. However, mean wind characteristics given in Table 3.2 can be assumed to characterize forcing conditions of wind associated with each synoptic weather type, thereby providing discrete periods of representative wind conditions at any location for which synoptic weather type calendars are constructed. An extremely small sample size of the FOR type in July gave a rather misleading northwest characteristic direction to that type; it should be understood that a northeasterly wind is more representative.

Synoptic weather type calendars have been prepared for both Lake Charles and New Orleans for the period 1963-1975. Muller and Wax (in press) have established that characteristic weather associated with the weather types is essentially the same at both places. This uniformity, on the average, establishes the credibility of extending these baseline data to areas along the immediate coast where no climatic data are available.

On this basis, synoptic weather type calendars were prepared by interpolation and extrapolation from the baseline calendars to nearby locations where water analyses were carried out.

Table 3.2

Mean Wind Properties of Synoptic Weather Types at New Orleans, 1971-1974*

Synoptic Weather Type	Wind Direction/Speed	
	January	July
Pacific High (PH)	33/6	--
Continental High (CH)	02/8	02/6
Frontal Overrunning (FOR)	01/10	31/7
Coastal Return (CR)	10/7	09/9
Gulf Return (GR)	15/9	15/6
Frontal Gulf Return (FGR)	18/9	24/5
Gulf High (GH)	33/6	26/6
Gulf Tropical Disturbance	--	10/7

*Wind direction in ten degrees of azimuth from 01 (10°=NNE) through 18 (180°= south) to 36 (360°= north). Speed in knots.

(modified after Muller, 1977)

Water budget calculations were employed in conjunction with the synoptic weather types to relate the effects of surplus fresh water to water level fluctuations. The water budget model developed by Thornthwaite (1948) and modified for daily computations on the computer by Yoshioka (1971) was further modified for use in wetlands environments of coastal Louisiana by Borengasser, et al (in press), who provided a detailed explanation of the modifications. Basically the alterations involved modified potential evapotranspiration (PE) estimates which provided higher PE in winter and lower PE in summer based on empirical experimentation with climatic conditions in this region; water availability over open water and marsh areas; differing soil moisture storage capacities by soil types; a two-layer soil moisture storage factor; rainfall intensity factors; and procedures to account for seasonal variation of all these factors. This modified water budget framework thus provided a much more representative and reliable estimate of the daily occurrence and distribution of surplus fresh water in areas of the coastal zone for which no measurements were available.

Water Level Data

Source and Condition:

Water level data used were taken from continuous strip charts obtained from the District Office of the U.S. Army Corps of Engineers in New Orleans. The data were recorded by automatic eight-day gauges installed and maintained by the Corps of Engineers or by the U.S. Coast and Geodetic Survey, National Oceanographic and Atmospheric Administration. Over fifty locations were available in the coastal region, and the degree to which the data were continuous and complete varied in both spatial and temporal aspects.

Water level data from nine of the locations were used (Fig. 1.1). The most complete records for any year were those for 1971. At every location except Eugene Island the records were very complete, consequently 1971 was chosen for analysis. The record for 1970 was used in the analysis at Eugene Island. Station location, extent of missing data, and period of record are shown in Table 3.3.

Table 3.3

Water Level Data Information

Station	Location	Missing Data (1971)	Period of Record
Lake Pontchartrain at Midlake (Mi) C.O.E. #85600	East side of Expressway, 11.6 miles north of south plaza	None	1957 to date
Bayou Chevreuil near Chegby (Ch) C.O.E. #82525	Borrow pit 300' north of Hwy. 20 bridge, 5.5 miles northeast of Chegby	None	1951 to date
Bayou Rigaud at Barataria (Ri) U.S.C. and G.S. #88400	Humble Oil Co. Dock	None	1947 to date
Bayou Petit Cocodrie near Cocodrie (Co) C.O.E. #76305	North bank, 600' west of junction with Bayou Petit Caillou	36 days	1969 to date
Eugene Island (EI) U.S.C. and G.S. #88600	East side of island in channel through Point au Fer Reef	None (1970)	1939 to date
East Cote Blanche Bay at Luke's Landing (LL) C.O.E. #88800	On dock 2.8 miles north of Bayou Sale entrance 2.1 miles south of South Bend	16 days	1957 to date
Vermilion Lock (VL) C.O.E. #76720	On north bank at east end of lock	None	1932 to date
Mermentau River at Grand Chenier (GC) C.O.E. #70900	On Hwy. 82 bridge	18 days	1956 to date
Hackberry (Ha) C.O.E. #73600	South bank of Black Lake Bayou, 600' west of junction with Calcasieu River	10 days	1943 to date

The nine stations were selected on the basis of data availability and relative location. They are representative of a broad range of coastal environments, for as Table 3.3 shows, these locations represent such diverse landscape features as a ship channel through a lake; bayous, marshes, and navigation canals that are open to natural drainage and that are blocked by dikes and weirs; bays and islands; enclosed drainage basins; and large lakes. Fresh, brackish, and saline environments are represented in the array of stations. Analysis of responses at these locations should provide a comprehensive view of the nature of relationships between water levels and recurring synoptic weather types and typical sequences of weather that describe the dynamic climate of the Louisiana coastal zone.

Periods of missing data occur for a number of reasons: hurricanes or flooding occasionally disrupt the records; the automatic gauges break down; mud and insects get into the equipment and stall it; pens run out of ink, paper rolls break, and operators sometimes forget to check or reset the equipment properly. The resulting records are not always complete and not always accurate. They are, however, the only records available, and they do represent the regime of water levels in the coastal wetlands.

Reduction:

Water level measurements were reduced by mathematical filtering to produce a water level record consisting only of fluctuations resulting from forcing by meteorological parameters. A 41-point filter verified and modified by Ormsby (1961) was used. This weighted "running-mean" filter suppressed diurnal and higher frequency oscillations in the water level record, and eliminated the periodic tidal cycles, but passed lower frequency, longer term variations. The fluctuations possessing longer periods that remained in the filtered water level record were assumed to represent the outcomes of meteorological conditions (Fig. 3.2)

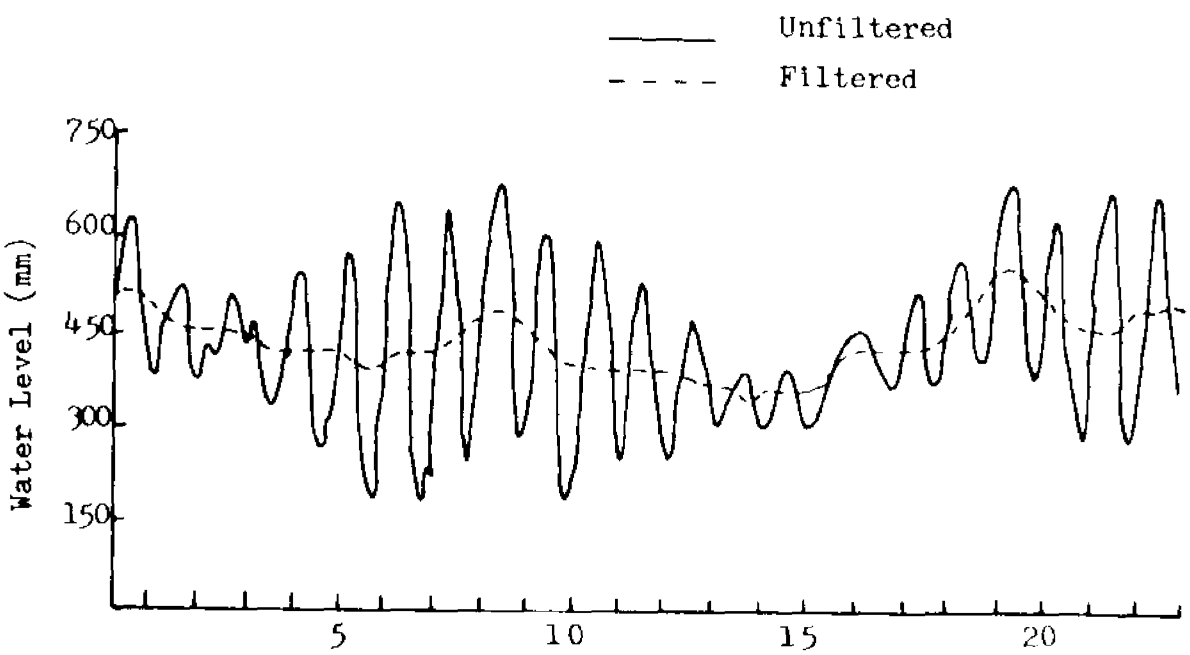

Figure 3.2: Variations in Water Level, Unfiltered and Filtered, Bayou Rigaud, October 1-23, 1971

A numerical filter was chosen instead of subtracting the predicted tide from the water level record because the filter offered a greater degree of tidal elimination and circumvented the necessity of determining tidal constants for each specific site. The filter used in this analysis was set to rapidly attenuate any variation in water level with a period less than 50 hours and to completely eliminate any variation with a period of less than 26 hours. It is, of course, possible that some meteorologically induced fluctuations had periods that were susceptible to the filtering and were consequently removed from the water level record along with the tidal fluctuations.

The sample interval employed was three hours, so each day had eight data points subjected to the filtering. The procedure was to determine the water level from the continuous record at three-hourly intervals, code and key-punch these data, then filter them to produce the continuous record of meteorologically induced variations in water levels. Since each point was filtered by a weighted running mean method utilizing 20 points ($2\frac{1}{2}$ days) on either side of the point, a missing datum caused loss of five days of mathematically accurate filtered water level record. Consequently, more days of record are missing in the analysis than the number stated in the raw data in Table 3.3.

Method of Analysis

Synoptic Weather Type Combinations:

Rarely will one of the synoptic weather types begin at 0600 and end 24 hours later. Therefore, in order to systematically cover 24 hour periods (0600-0600), the synoptic weather types thought to produce the same type of water level change were grouped into combinations. The combinations listed below were utilized in the analyses:

Combination 1 -- CR, GR, or FGR changing to FOR, PH, CH, or GH (cold front passage)

Combination 2 -- Pacific High (PH) and Gulf High (GH)

Combination 3 -- Continental High (CH) and Frontal Overrunning (FOR)

Combination 4 -- GH, PH, CH, or FOR changing to CR

Combination 5 -- Coastal Return (CR)

Combination 6 -- Gulf Return (GR) and Frontal Gulf Return (FGR)

Combination 7 -- GH, PH, CH, FOR, or CR changing to GR or FGR (warm front passage)

Combination 8 -- Gulf Tropical Disturbance (GTD)

Combination 1, representing a cold front passage, should be expected to decrease water levels as should combinations 2 and 3 since they are associated with west to northeast winds. Combination 4 is associated with winds veering gradually from northwest to east or southeast, so water levels should increase. Combinations 5 and 6 should produce rising water levels since they are associated with winds from east through south-southwest. Combination 7 represents a sequence of weather type changes through the 24-hour period which can best be described as passage of a warm front over the location; it should be understood that it is only necessary for one or more of the five synoptic weather types to occur before passage of the warm front. Water levels should tend to increase during Combination 7. There are no preferred wind directions associated with Combination 8 because tropical disturbances can approach the basin from all directions except northwest through northeast. However, the largest, most rapid, and most damaging changes in water levels in the coastal region are produced by storm surges and intense rainfall associated with hurricanes. Maximum surge heights between 10-24' have been recorded along the Gulf Coast (C.O.E., 1976). Therefore, because of the severity of water level changes and the extreme stages of water level produced, the GTD weather type is an important, although infrequent, part of the coastal water level regime.

Comparative Analysis:

Analysis of the relationship between a synoptic weather type and the resulting water level response was initiated by tabulating the daily changes in filtered water levels (0600-0600) by weather type combinations. Each 24-hour period was assigned to one of the weather type combinations. Changes of less than 60mm were assumed to be meteorologically insignificant and were not recorded for summation. Negative changes and positive changes were separated, and days with fresh water surplus, determined by water budget computations, were separated from days with no surplus. Individual water level fluctuations, grouped into these categories, were summed over the entire year.

This procedure assessed all water level changes for the year, in surplus and nonsurplus situations, up or down, within each synoptic weather type combination. Graphing the accumulated fluctuations revealed a pattern of responses to each synoptic weather type. Ratios of positive change to negative change were calculated for each combination at each location to provide a measure of the relative strengths of the relationships. An averaging of responses to each synoptic weather type at each location produced a regional mean response to each synoptic weather type and established the probable reaction of water levels along all or any part of the coastal zone under the influence of any of the weather types.

Quantitative analysis was then utilized to assess variability of responses observed in three classes:

1) all responses observed in the entire region to each synoptic weather type combination;

2) responses to all weather events observed collectively at each location; and

3) all responses to each synoptic weather type combination observed at each separate location.

Statistical comparison and evaluation of the data grouped into these classes was used to detect the existence of significant differences among responses within each of the three classes. Additionally, responses within these classes were tested for significant differences by season. These procedures provided more detailed and more accurate insight into the distinctive characteristics of the relationships established.

Correlation and Regression analysis could have been used to evaluate the degree of mutual correspondence between water level changes and separate meteorological elements such as wind speed, direction, or duration. That procedure would have allowed predictions of water level change for given wind conditions or any other parameters the analyses were developed with. However, the objective of this research was not to predict absolute water level change based on a single element of the weather conditions, but rather to assess responses of water levels to the totality of weather in a number of locations where single element data are unavailable and to assess differences in responses to different weather types and at different locations. Therefore, correlation and regression analysis was deemed inappropriate.

A completely randomized design analysis of variance (ANOV) with factorial arrangement of locations on synoptic weather type combinations was the statistical test employed to locate significant differences, and Tukey's test of specific hypothesis was used to determine exactly where the differences existed within each class (Steel and Torrie, 1960). For example, when the analysis of variance (ANOV) detected highly significant differences among responses of water levels to the synoptic weather types or among locations or among seasons, tests of specific hypothesis revealed exactly where the variation was, or in other words, exactly which of the weather types or locations or seasons provoked a response that was different from responses caused by the other weather types, locations, or seasons, and how different that response was.

To assess the relationships in different environments across the coastal zone, nine locations were analyzed for one year. Mean responses to each synoptic weather type combination were used to summarize spatial variability of the responses graphically. One station was analyzed for a period of 10 years to assess the relationships temporally.

Summary of Assumptions

Assumptions on which the procedures are based are summarized as follows:

1) The synoptic weather type calendars and water budget calculations provide reasonably representative spatial and temporal occurrences of climatic phenomena.

2) Filtered water level changes represent meteorologically driven fluctuations.

3) The arbitrary 60mm threshold for observations is sound.

4) For the statistical analyses, effects of the different fixed factors (synoptic weather types, locations) are additive, and errors incurred in sampling are normally and independently distributed with the same variance.

The methods used and assumptions made in the analysis have been described in this chapter. A table of abbreviations and symbols used throughout the discussion of the analysis is included as Appendix A. The following chapter discusses the results of the analysis and describes the degree to which the objective of the research was attained.

CHAPTER IV

RESULTS OF REGIONAL ANALYSIS

Introduction

The purpose of this analysis is to determine whether or not a pattern of relationships between weather and water level responses exists in the coastal zone. In accomplishing this objective, answers must be obtained to a number of questions. For instance, if these relationships are measurable, what are they, and how strong are they? Are they similar throughout the Louisiana coast, or do different locations and environments produce responses so different from each other that no average regional response can be identified? Is the response to each synoptic weather type combination constant at each location, and do the responses vary seasonally? These questions are addressed by analyzing the daily fluctuations in water levels exhibited at the nine different locations selected for analysis along the coast (Fig. 1.1).

The discussion that follows relates the interpretation of the analyses from two different but complementary perspectives:

1) the first part of the chapter is devoted to the graphical analyses from which the relationships were determined and evaluated; and

2) the latter part of the chapter describes the statistical assessment of each relationship's characteristics and validity

through rigorous analyses of the classes of responses set forth in Chapter III. Finally, the information acquired from both these perspectives is summarized.

Derivation of Mean Regional Relationships

Graphical analyses of the relationships between synoptic weather types and water level fluctuations during 1971 illustrated that water levels respond strongly and in a relatively consistent manner to meteorological inputs associated with the synoptic weather types. Although the hypothetical responses set forth in Chapter III were not observed in every case, 80% of the observations (n=1666) did fit the predicted pattern. Occurrence of the predicted responses found in the individual analyses ranged from 65 to 80% of the samples, and the number of observations in the samples for the individual locations ranged in number from 80 to 264.

When the accumulated fluctuations at all nine locations were summed and averaged by synoptic weather type combination, the resulting pattern established the average response of water level to meteorological forcing (Fig. 4.1). The resulting pattern confirmed the existence of strong relationships for each of the synoptic weather type combinations. Combinations 1, 2, and 3 generally lowered water levels, and combinations 4, 5, 6, 7, and 8 raised water levels.

Caliber of the relationships established for each synoptic weather type combination is indicated by the ratios of the responses and by the pattern of the overall mean responses. For example, combination 1, a cold front passage, lowered water levels at ratios of

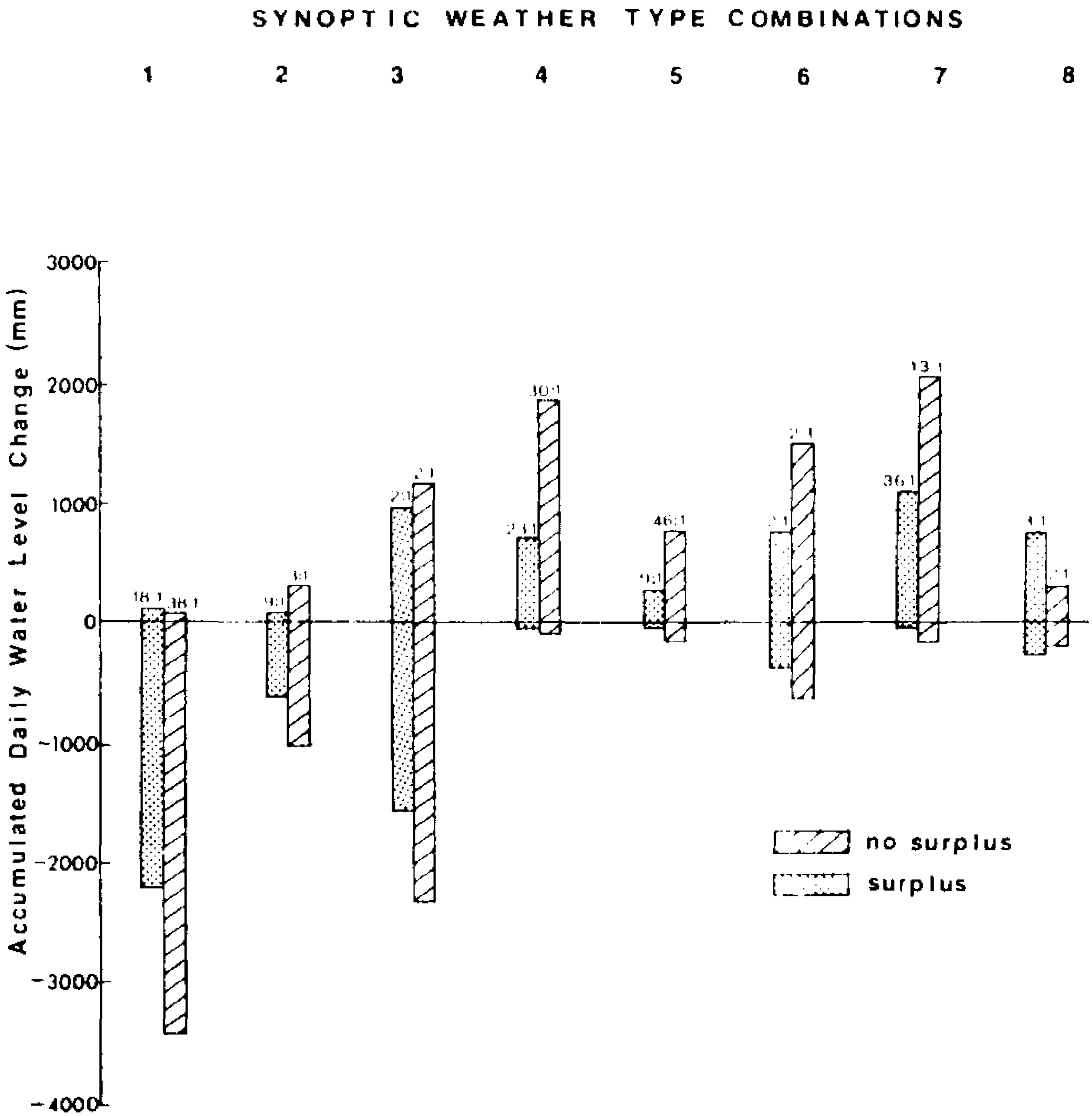

Figure 4.1: Average Response of Water Levels
to Synoptic Weather Types,
Coastal Louisiana

38:1 (3444 mm down to 91 mm up) under nonsurplus conditions and 18:1 (2194 mm down to 122 mm up) under surplus conditions, whereas combination 4, representative of winds changing from northerly to easterly or southeasterly, raised water levels at ratios of 30:1 (1859 mm up to 61 mm down) and 23:1 (701 mm up to 30 mm down). Combination 1, representing initiation of northerly winds, showed consistently firm relationships; but combination 3, typically the weather following a cold front and representing sustained northerly wind flow, showed much weaker relationships (2:1, 2:1). Likewise, combination 7, a warm front passage initiating southerly winds, showed strong relationships (36:1, 13:1); yet the continuation of that southerly flow, represented by combination 6, showed the same weakening of the relationships (2:1, 2:1).

These characteristics indicate that initial responses of water level to meteorological forcing are much sharper than responses to that same forcing when it is sustained. In other words, the forcing function of the weather type decays, and forces other than meteorological become dominant when a weather type persists over the region. It is the changing of weather types that introduces the greatest meteorological forcing into the system, providing impetus for the processes that produce fluctuations in water levels. This impression is strengthened by the firm relationship established in response to combination 4, also representative of changing weather.

The concept of steady-state, or dynamic equilibrium, may be useful in explaining the apparently weaker relationships associated with the occurrence of sustained weather conditions over the region. According to this concept, water level will reach a maximum set-up for the wind that is causing it, limited by fetch and duration of the wind. The water absorbs as much energy as it can from wind of that velocity and an extension of either fetch or duration will not produce a larger set-up. As suggested by the information in Table 4.1, wind velocities associated with the synoptic weather types and pertinent to this analysis (Table 3.2) produce maximum set-up in less than 24 hours.

Table 4.1

Minimum Fetch and Duration Required for Full Development of Set-up Associated With Various Wind Speeds

Wind (kts)	Fetch (km)	Duration (hrs)
10	18.5	2.4
20	140	10
30	520	23
40	1320	42
50	2570	69

(modified from Bascom, 1964)

Since this analysis is based on 24-hour time units, maximum set-up is likely reached during the initial 24 hours of a weather type's occurrence. Thereafter, as wind speed associated with the prevailing weather type decays with duration, the system of balance is disturbed and continually adjusts to meet the requirements of the new conditions. This produces a series of stages of equilibrium with constantly decreasing inputs of energy from the meteorological elements, and gradually allows other forcing agents such as tides to overcome the effects of the weather conditions.

Figure 4.2 illustrates this principle using observations of water level change at Bayou Rigaud. In the figure, filtered water level is plotted over five days of CH weather type. Water level falls about 95 mm during the initial 24-hour period, but even though water level remains depressed, no further significant lowering is produced throughout the duration of the weather type. Evidently steady-state conditions are attained rapidly, accounting for the well-defined anticipated response observed during changing and initial weather conditions. However, the duration of the weather type produces only the marginal relationships observed during sustained weather conditions.

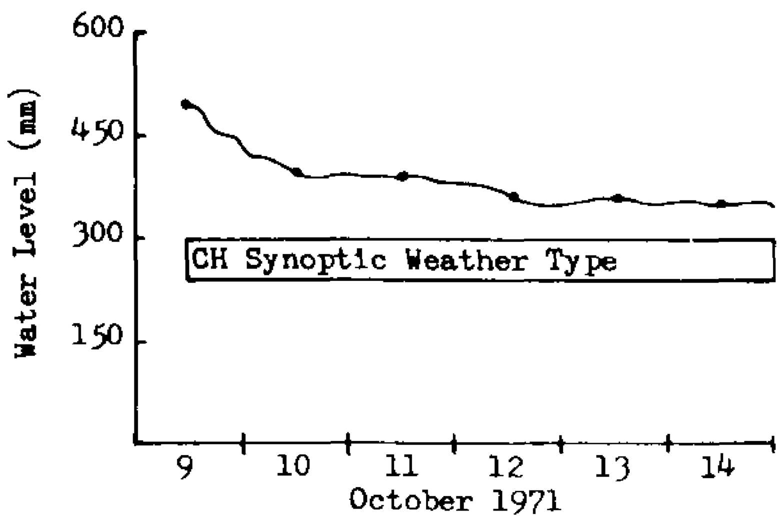

Figure 4.2: Change in Filtered Water Level at Bayou Rigaud, October 9-14, 1971

It was anticipated that decreases in water levels would be lessened by the presence of surplus water, and that water levels increasing as a result of meteorological forcing would be augmented by surplus water. These relationships were not consistent when averaged for all the locations, even though they were present in widely varying intensities at several of the individual locations. For instance, although combination 1 showed the predicted relationship, a 38:1 nonsurplus situation decrease but only an 18:1 surplus situation decrease, combination 2 showed the opposite result, a 3:1 decrease when no surplus was present but a 9:1 decrease when surplus was available.

Mean responses for both nonsurplus and surplus conditions fit the expected pattern without exception, thus reinforcing the establishment of the anticipated relationships. Larger average responses for combinations 1, 4, and 7 verify the premise that changes of weather types are most forceful in producing environmental response.

Moreover, the established pattern of response to the synoptic weather type combinations, surplus and no surplus conditions, reveals a logical succession of responses to a continuum of weather. For example, a typical sequence of weather along the Gulf Coast includes northerly circulation (combinations 1, 2, and 3) changing to easterly (combinations 4, 5), then to southeasterly-southerly (combinations 6 and 7), then back to combination 1 again. The expected and probable regional responses, as established by this analysis, are decreasing water levels (combinations 1, 2, 3) followed by increasing water levels (combinations 4, 5, 6, and 7). It is important to note that these fluctuations are in addition to the periodic tidal fluctuations and are related solely to variability of the climate, as indexed by variability of the synoptic weather types through time. Therefore, the more rapid or more often the succession of the synoptic weather types occurs, the greater the amount of forcing applied by climatic components to water level changes becomes.

The validity, and consequent usefulness of these established regional responses, lies in 1) the representativeness of the data, 2) the accuracy of interpretation, and 3) the degree of confidence placed in the assumptions made in developing the analysis. Selected aspects of the analyses of individual locations are presented next to show how the relationships established at the different locations varied in relation to each other and to the average regional relationships developed from compilation of the individual analyses.

Assessment of Individual Location Relationships

Local shoreline configuration and terrain at each site affect the responses of water levels to weather events, imparting some unique characteristics to the relationships at each separate location. These dissimilarities in turn modify the regional average relationships. Therefore, some aspects of the analyses of each site deserve examination to enable the reader to judge the quality and content of the postulated regional responses.

Bayou Rigaud:

The strongest and most consistent relationships established were those found at Bayou Rigaud (Fig. 4.3). Strengths of the established relationships are evident, and the pattern of responses shows that most relationships there are better than the overall averages. Combinations 1, 4, and 7 demonstrated no departures from the expected results.

Of the 113 observations used in the analysis at this location, 89% were in the predicted direction, the highest percentage of all the nine locations analyzed. Every mean response was in the expected direction, but the anticipated effects of surplus water were not strongly established. For example, combination 3 showed a 5:1 decrease on nonsurplus days but a 16:1 decrease on surplus days, the opposite of expected response. Combination 6 shows a 3:1 increase on nonsurplus days, but about equal increases and decreases on surplus days. It is reasonable, however, to expect that surpluses would have little or no effect on water levels in open bay waters as contrasted to the significant effect surplus has on water levels in a constricted basin.

Hackberry:

The Hackberry location is unique among all the sites chosen for analysis because of its geographic setting. The water level gauge is located in a bayou that is affected by water level changes in open marsh to the west and open lake to the east, by constricted tidal flow from the south, and by the influence of a relatively large river system to the north. Additionally, although the lake itself is an average of only 3 to 4 feet deep, it is modified on its western margin

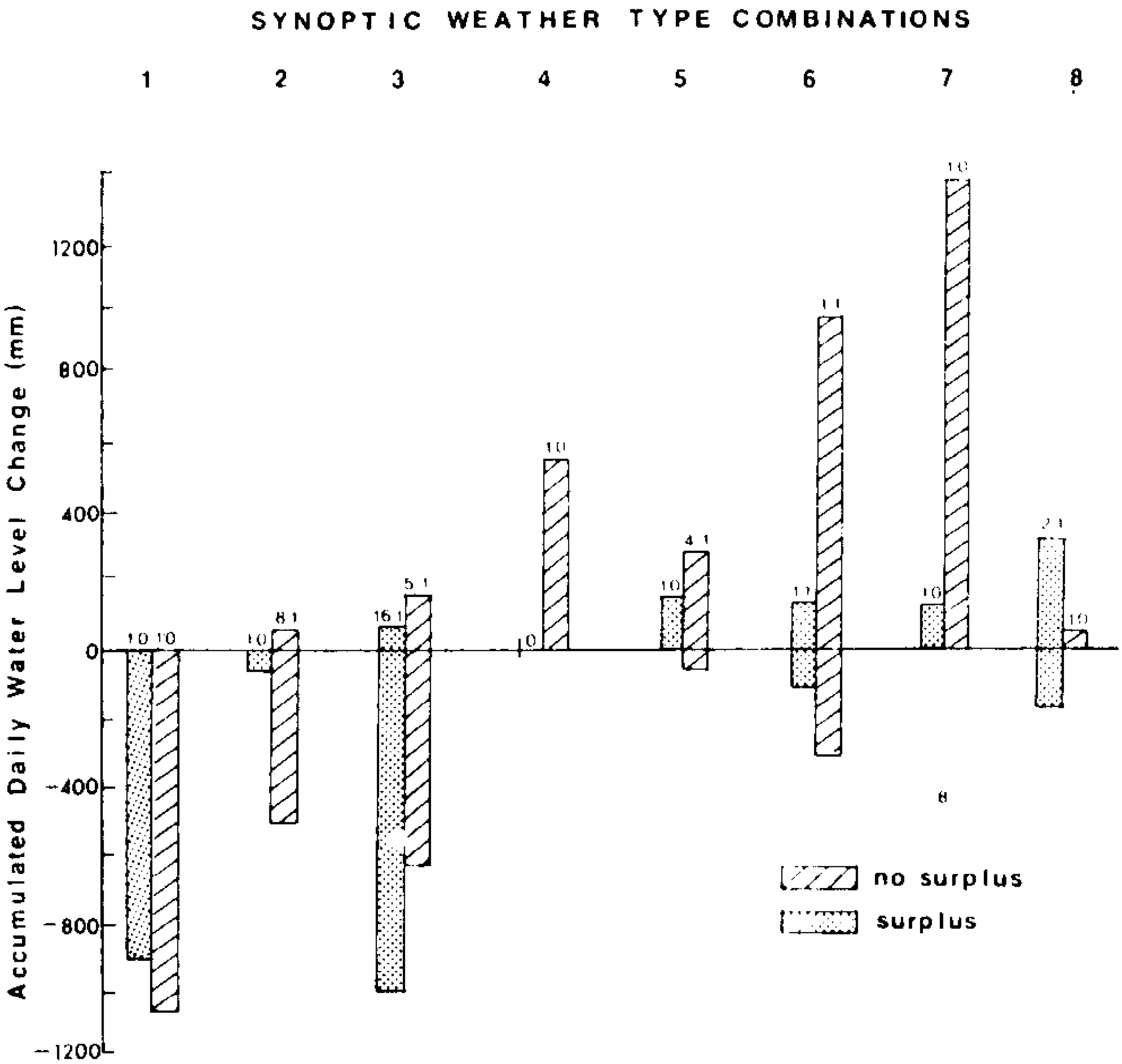

Figure 4.3: Response of Water Levels to Synoptic Weather Types, Bayou Rigaud

by the 30-40 foot deep Calcasieu Ship Channel and related spoil banks. The interference of this channel with the measurement of natural functions and responses at this location, and also the impact of the river regime need to be considered in assessing the result of the analysis performed there.

Of the 200 observations used in the analysis at Hackberry, only 65% showed the expected response (Fig. 4.4). The relationships established there were the weakest of all the locations analyzed. As can be seen in the figure, the weakest relationships are shown in the responses to combinations 2, 3, and 6, in which water levels showed an almost equal tendency to change in either direction. However, all the mean responses were in the predicted direction of change except those in combinations 3 without surplus and 8 with surplus. Therefore, the anticipated overall pattern of responses was established.

Combinations 2, 3, and 6 represent relatively steady-state winds; the decreasing effects of such sustained wind conditions on the relationships with water level response have been previously described. The response to combination 3 is especially interesting. The frequency of changes in water level greater than 60mm, and especially the high incidence of a positive change of water level during this type of weather, in contradiction to the expected response, suggest several explanations for the seemingly anomalous responses found there.

Strong influence from the river regime is indicated. Concen-

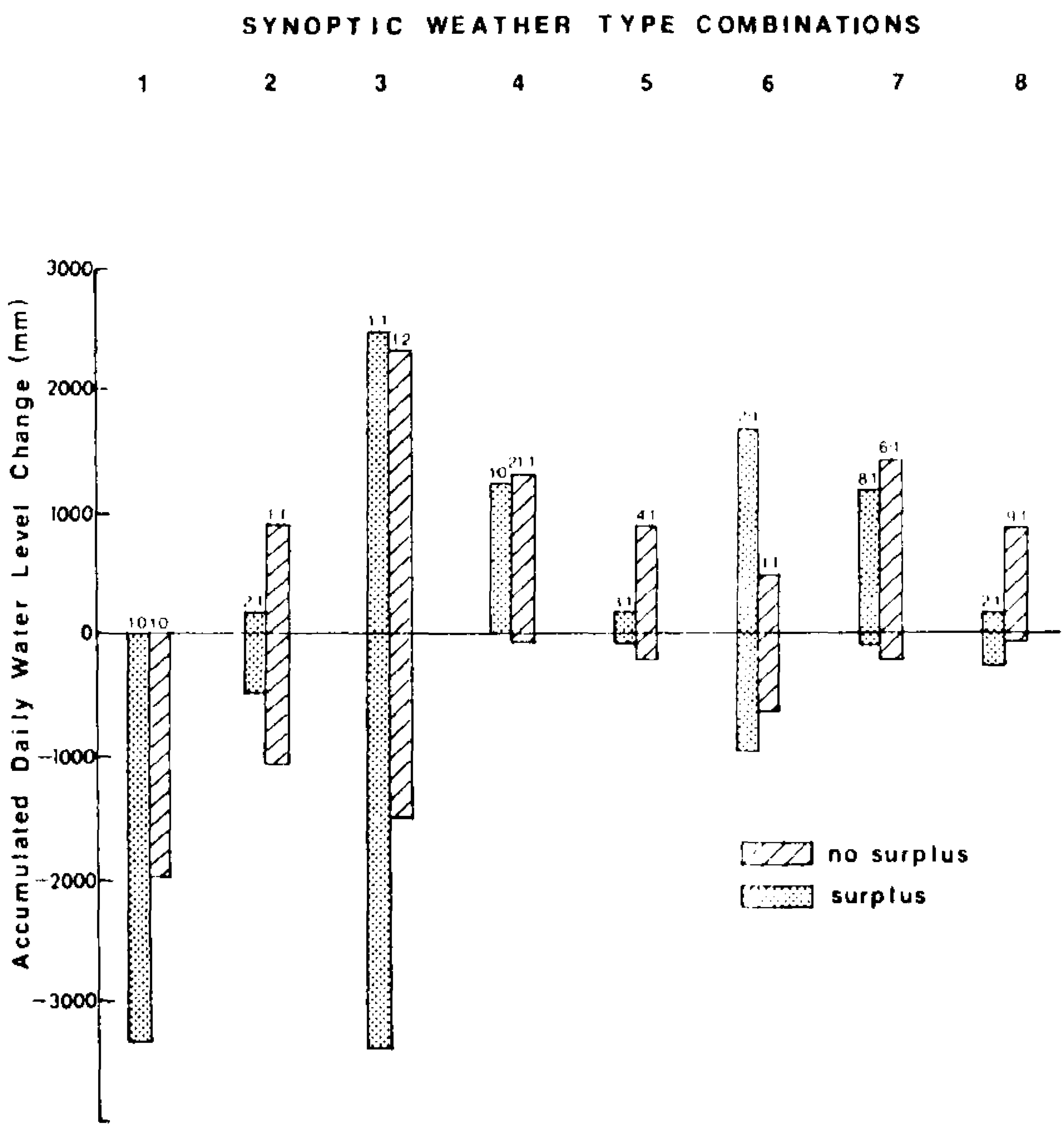

Figure 4.4: Response of Water Levels to Synoptic Weather Types, Hackberry

tration time of the river basin remains to be evaluated because in the circumstances associated with combination 3, runoff might arrive at the lake several days after passage of cold fronts and rainy weather. There is also a possibility that river water tends to accumulate in the lake when northerly winds pile water up against the southern end of the lake, flooding the constricted outlet and causing a "bottleneck" in the flow out of the lake. Both these explanations offer possible reasons for the weakness of the relationships established for the occurrence of the type of weather associated with combination 3.

Other Locations:

Analyses of the two foregoing locations were singled out for detailed discussion because they represent the "best" and "worse" of the individual analyses constituting the regional analysis. Furthermore, discussion of location characteristics of these two sites focused attention to the impact of diverse terrain and geographic situation as it related to input from driving forces other than meteorological.

Analyses of water level responses to synoptic weather type combinations at the remaining seven locations are not described in detail because so much repetition was found in the responses. Also, variation in character of the responses to synoptic weather type combinations was determined by statistical analysis and is described in detail in the following section of this chapter.

Nevertheless, figures 4.5 through 4.11 confirm that the anticipated patterns of water level response to synoptic weather type com-

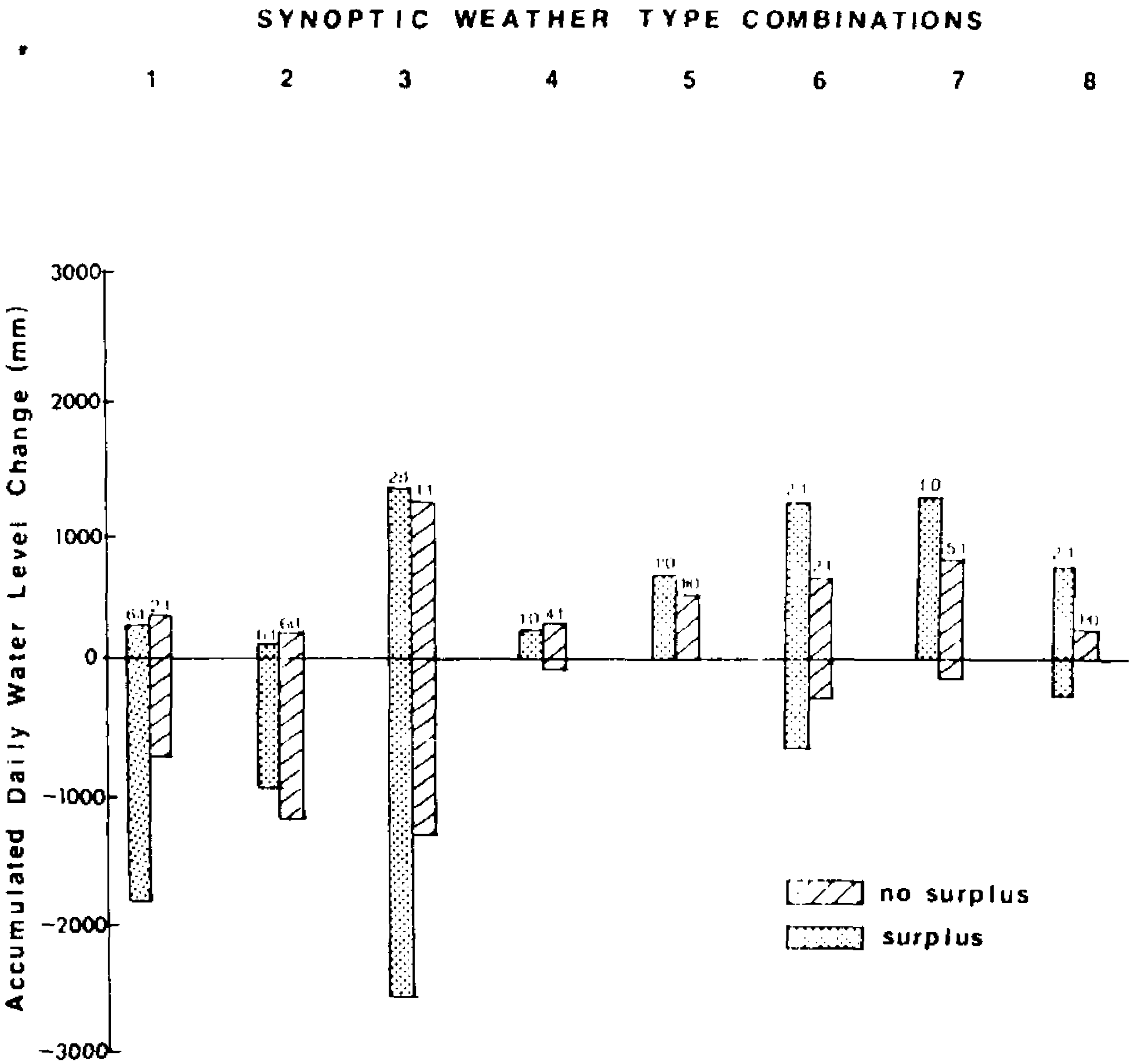

Figure 4.5: Response of Water Levels to Synoptic Weather Types, Midlake

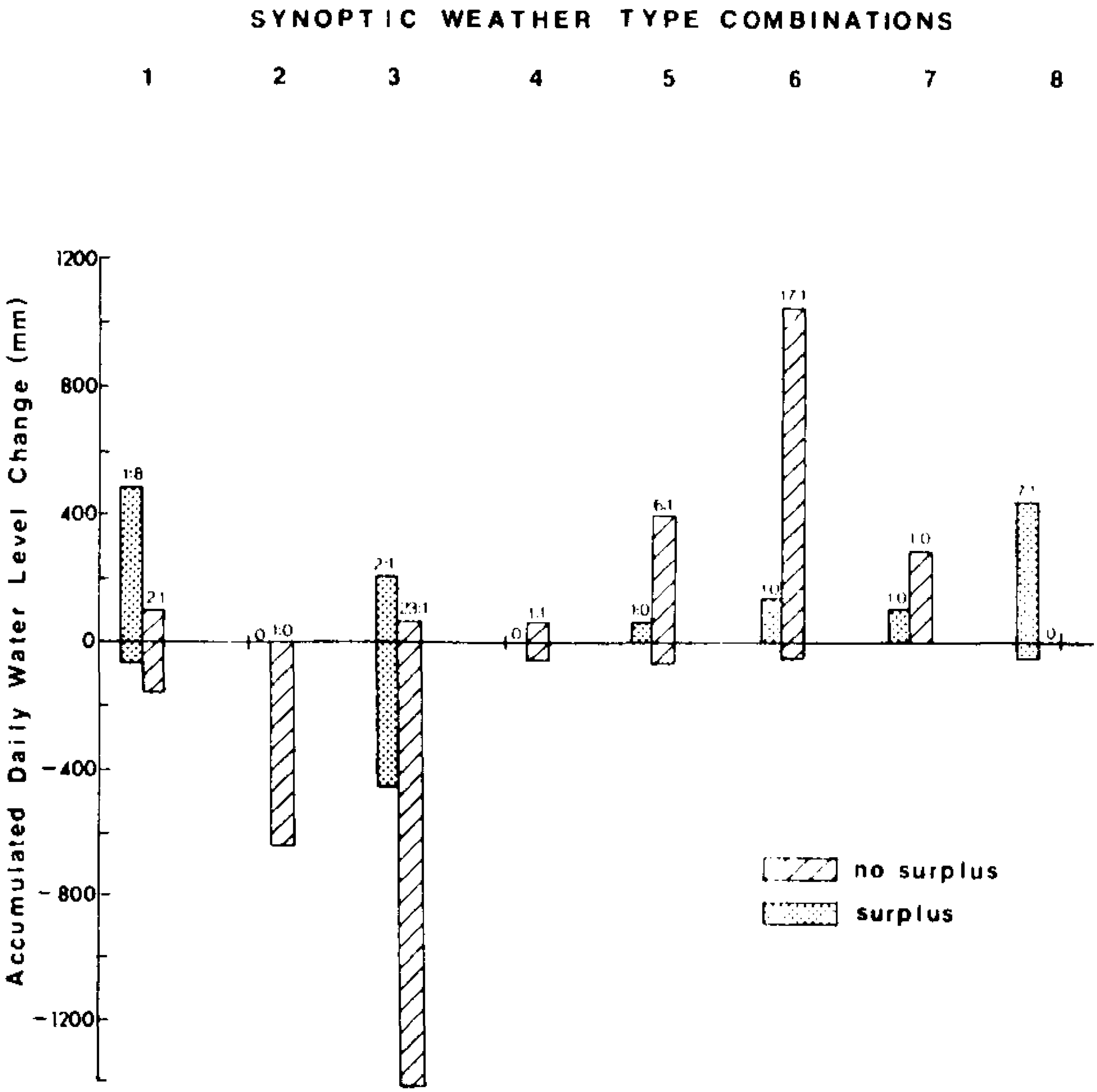

Figure 4.6: Response of Water Levels to Synoptic Weather Types, Chevreuil

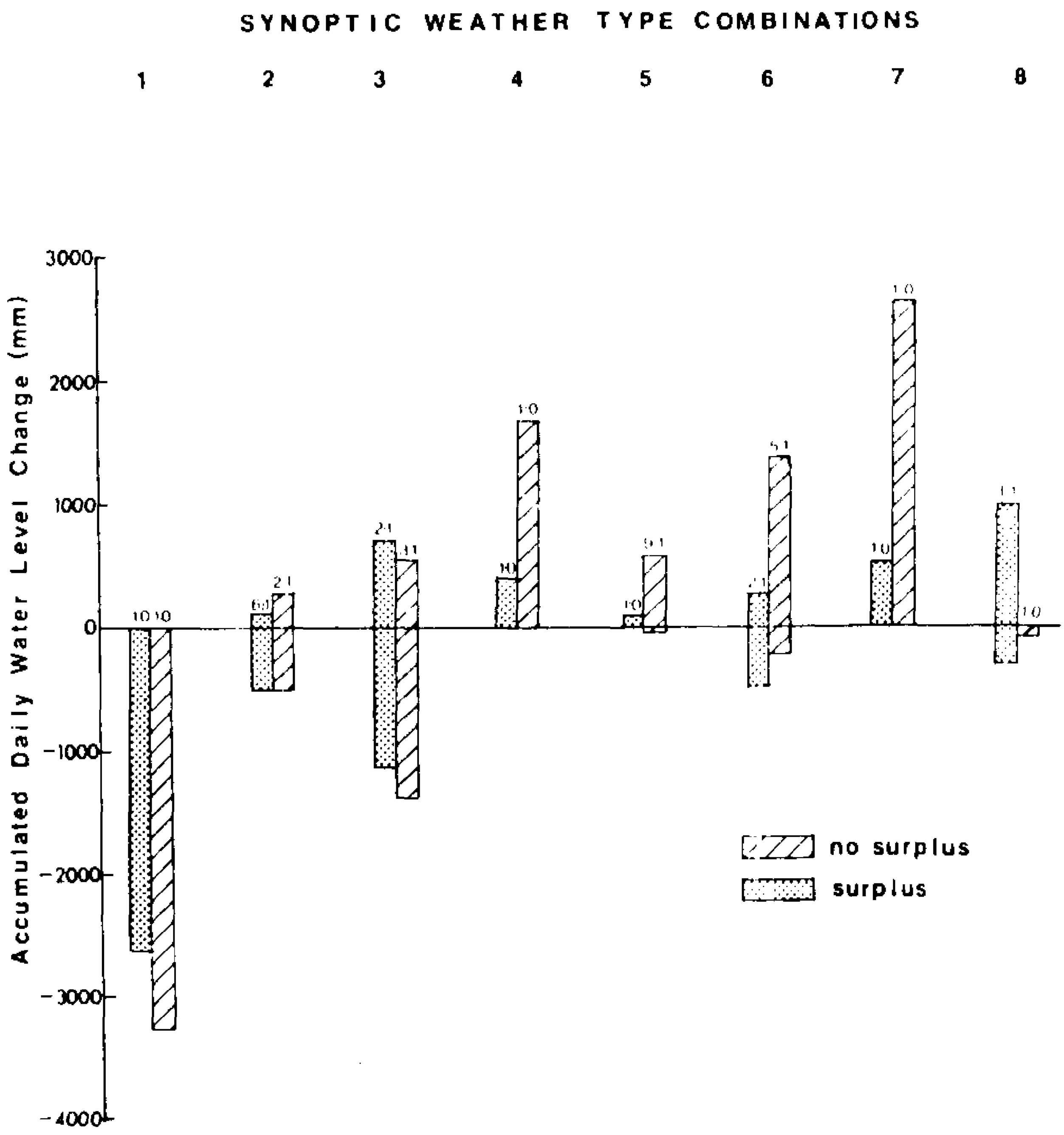

Figure 4.7: Response of Water Levels to Synoptic Weather Types, Cocodrie

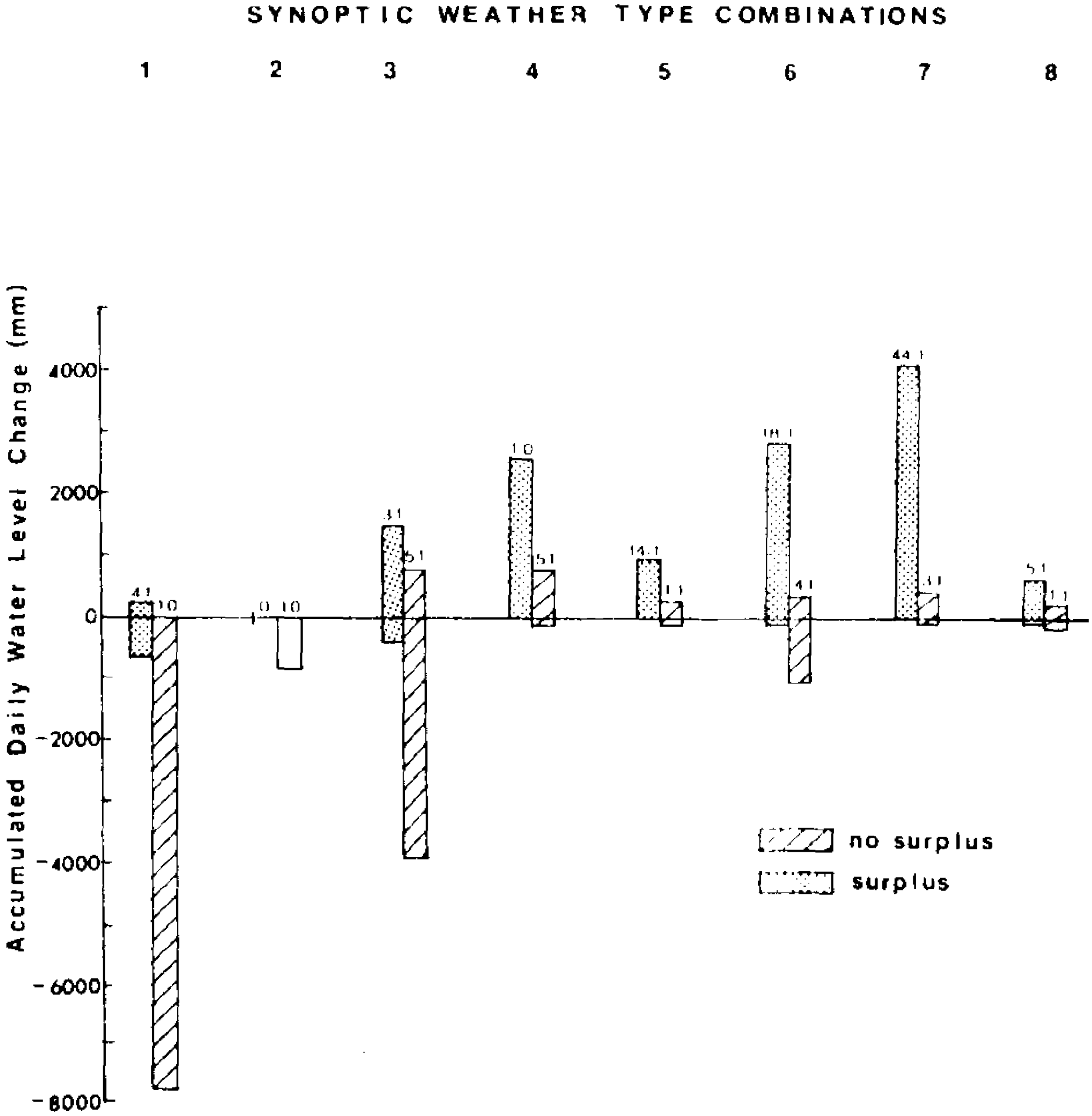

Figure 4.8: Response of Water Levels to
Synoptic Weather Types,
Eugene Island

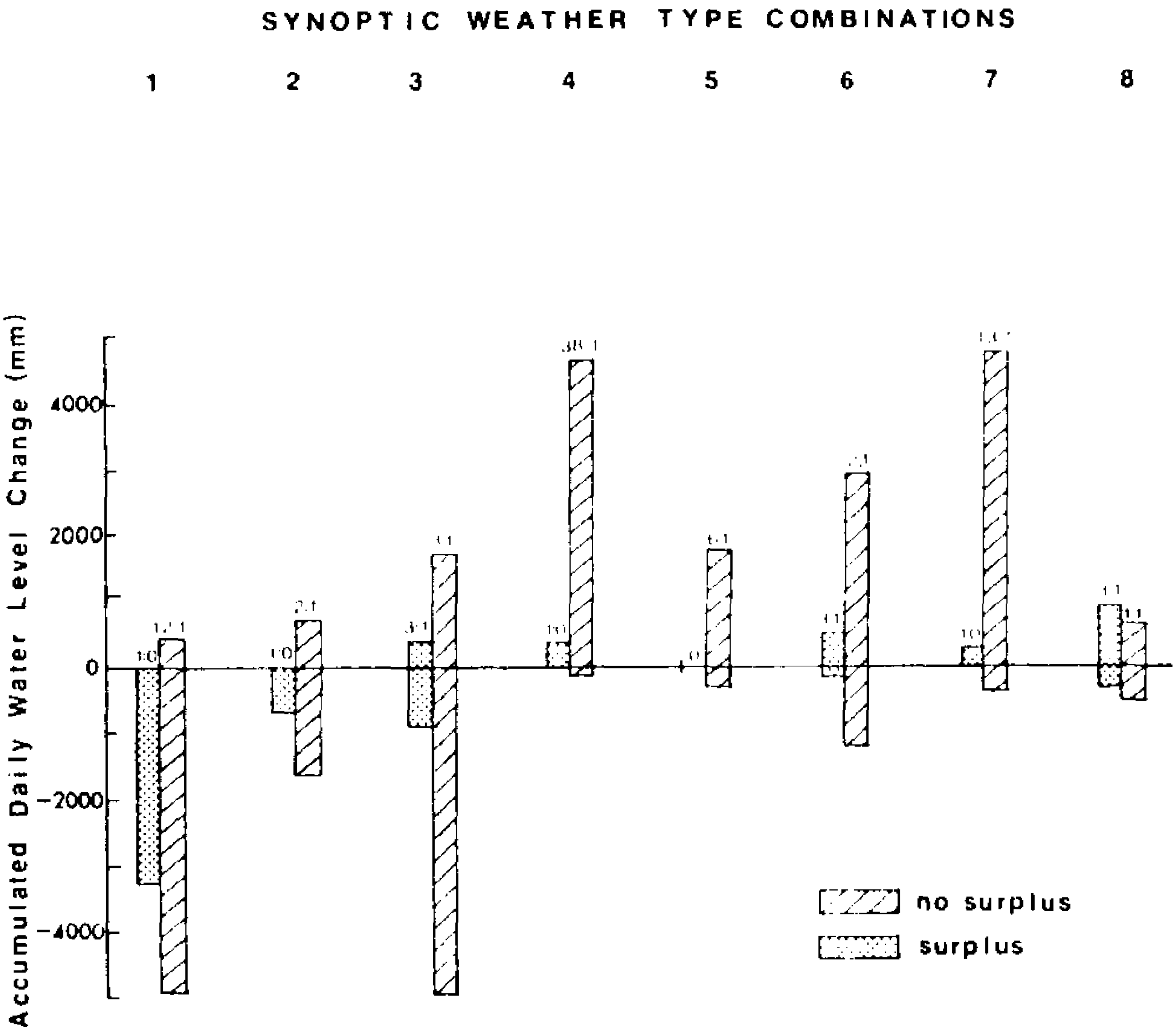

Figure 4.9: Response of Water Levels to Synoptic Weather Types, Luke's Landing

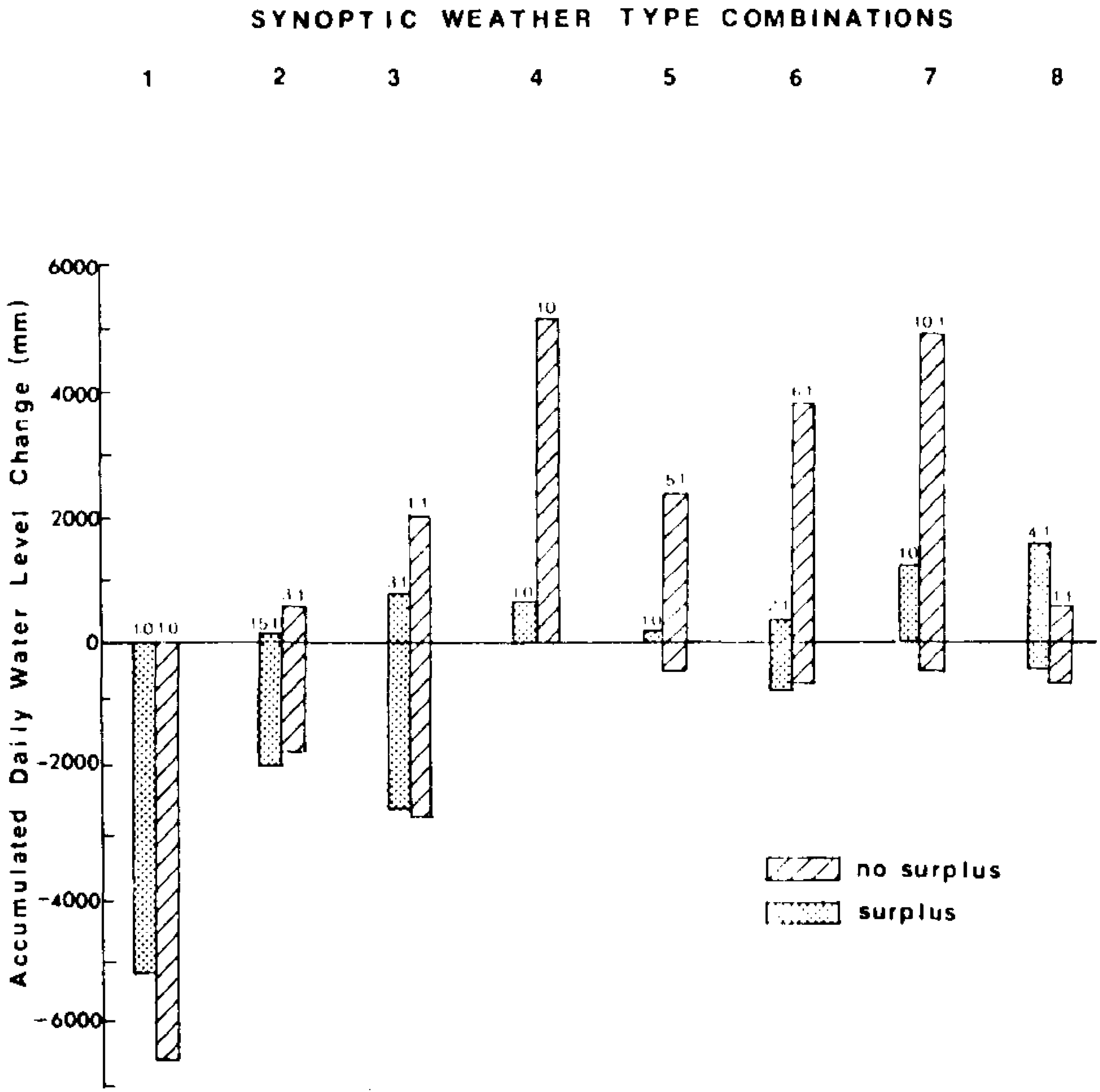

Figure 4.10: Response of Water Levels to Synoptic Weather Types, Vermilion Lock

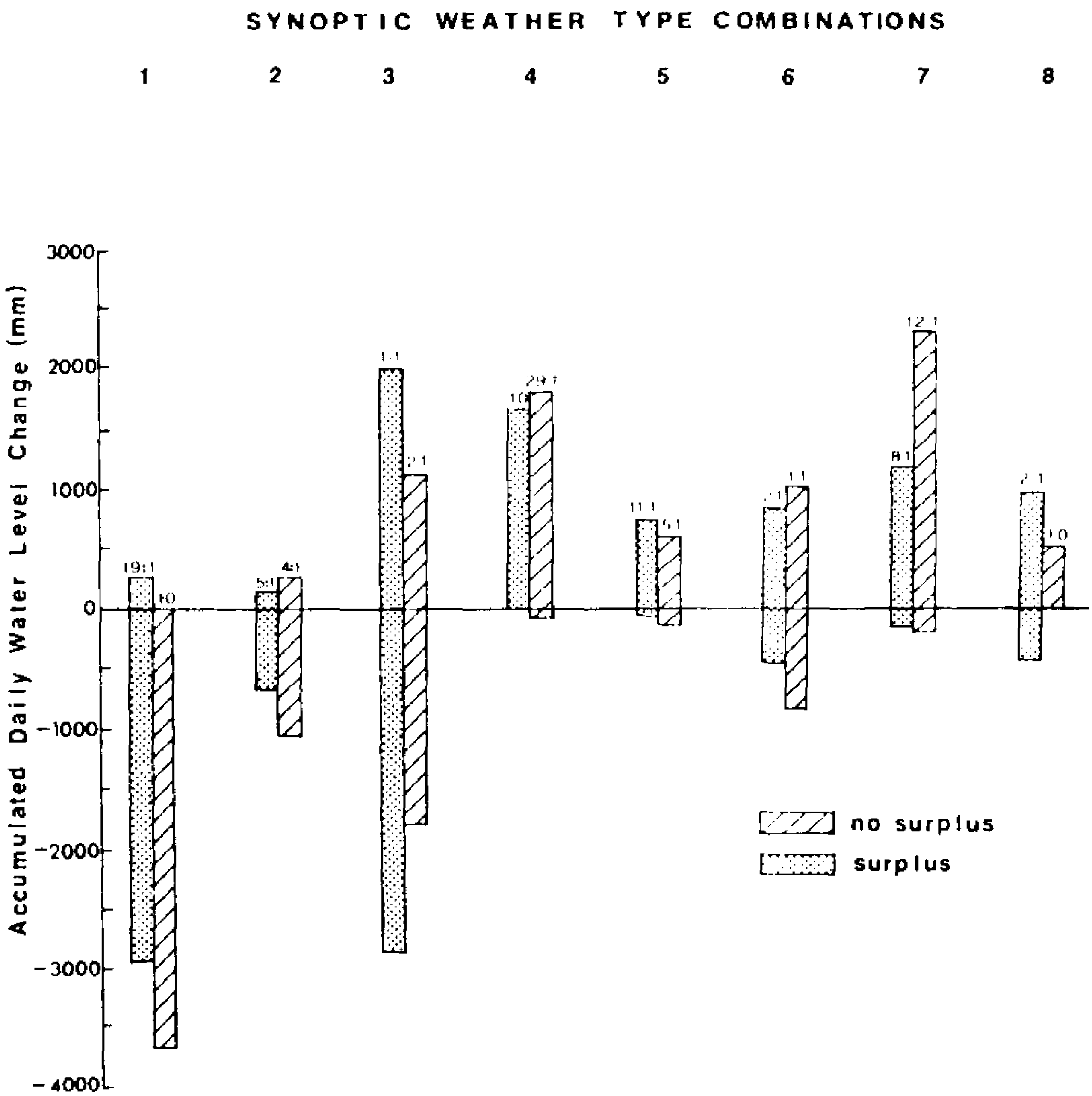

Figure 4.11: Response of Water Levels to Synoptic Weather Types, Grand Chenier

binations were established at every location, and they also demonstrate the spatial variability of the strengths of the relationships. Mean responses to each synoptic weather type combination were in the expected direction with seven exceptions:

Combination 1, surplus at Chevreuil (Fig. 4.5)
Combination 3, surplus, at Eugene Island (Fig. 4.7)
Combination 3, nonsurplus, at Hackberry (Fig. 4.3)
Combination 6, surplus, at Cocodrie and Vermilion Lock (Figs. 4.6 and 4.9)
Combination 6, nonsurplus, at Eugene Island (Fig. 4.7)
Combination 8, surplus, at Hackberry (Fig. 4.3)

Passage of a cold front (combination 1) with surplus evokes a response at Chevreuil different from any other location. This anomaly will be discussed at length in Chapter V. The positive mean response to combination 3 with surplus at Eugene Island indicates probable overriding of meteorological driving forces by discharge of the Atchafalaya River following passage of a cold front there, similar to the response found at Hackberry for the same weather conditions.

Circulation developing in Atchafalaya Bay as a response to combination 6 (sustained southerly air flow) could explain the anomalous mean negative response to that weather type at Eugene Island. Since the circulation in the bay is predominantly westward and since discharge from the Atchafalaya River is decreasing during weather conditions associated with combination 6, nonsurplus, water levels could logically decline at the site of the water level gauge, even though in opposition to the established regional response. This may represent a case where the effects of local features overcome the regional response. No explanation is offered for the mean negative response to combination 6, surplus, at Cocodrie and Vermilion Lock, especially since the nonsurplus situations for that weather type show such strong positive responses (5:1 and 6:1, respectively).

Previously described geographic surroundings at the Hackberry location may explain the negative mean response to Gulf tropical disturbances with surplus. Every other location showed a positive response to this weather condition, so that was established as the preferred regional response. However, precipitation produced during that weather type may not reach the Hackberry gauge site during the period classified Gulf Tropical Disturbance (GTD) because of the size and characteristics of the drainage basin.

The westernmost location of this site may also offer some explanation for the anomalous response. The eye of Hurricane Edith in September of 1971 passed between Hackberry and all the other locations to the east, causing continuous northerly and northeasterly winds at that location, but easterly and southeasterly winds at the other locations. That phenomenon would have had enough effect on the small samples from the GTD weather type to have caused a negative mean response at the Hackberry site. At 0900 CST on September 16, stage was 2.7' at Hackberry, 5.9' at Grand Chenier, 4.8' at Vermilion Lock, 3.9' at Luke's Landing, and 3.7' at Cocodrie.

The importance of location on response of water level to the GTD weather type can be further emphasized by the example of Hurricane Carmen in 1974. That storm moved inland in the Weeks-Avery Island area. East of that point water levels rose because of strong southerly winds (5' above normal in Lake Pontchartrain and 3-4' above normal in Lake Borgne and lower reaches of the Mississippi River) but west of that point northerly winds caused low stages (2' below normal in Vermilion Bay-Cote Blanche Bay area). A high water mark of 11.64' (over 10' above normal) was recorded at Cocodrie (C.O.E., 1975).

Variability of Relationships by Location

Table 4.2 summarizes salient information about response characteristics found at the separate locations. It should be emphasized that values in Table 4.2 represent responses averaged for all weather types collectively, separated into surplus (S) and nonsurplus (NS) situations. The mean responses in the table are therefore the averages of all observations in each of the surplus categories, and the range of responses given is the range between the largest negative and the largest positive response observed at each location regardless of weather type. The information was calculated using the entire spectrum of weather at each location and is consequently not related to the occurrence of separate weather types, but rather to location alone.

Several substantial points of interest are evident in the table. One important inference drawn from the information is the difference in magnitude of response to similar weather at each of the locations. As demonstrated in the table, the number of observations as well as the size of mean responses was generally greatest at the locations in the central part of the coastal zone and less at the locations in

Table 4.2

Summary of Response Characteristics
of Individual Locations

Location	Number of Observations		Mean Response (mm)		Range of Responses (mm)		% Expected Responses
	NS	S	NS	S	NS	S	
Midlake	81	104	2	-5	-335 to 152	-460 to 274	73
Chevreuil	57	23	-8	36	-244 to 213	-122 to 152	84
Rigaud	79	33	8	-41	-183 to 152	-152 to 122	89
Cocodrie	108	57	13	-40	-427 to 305	-488 to 335	84
Eugene Island	122	105	-95	102	-488 to 488	-335 to 549	83
Luke's Landing	189	41	16	-69	-579 to 579	-762 to 335	84
Vermilion Lock	185	77	32	-76	-579 to 549	-762 to 518	84
Grand Chenier	110	95	-2	2	-457 to 396	-732 to 427	76
Hackberry	114	86	17	-16	-305 to 335	-640 to 670	65

NS = nonsurplus conditions
S = surplus conditions

both eastern and western extremities of the region. For instance, although the data are not presented in the table, total water level change induced by meteorological forcing during the year at the Chevreuil location was only 6309 mm, yet accumulated changes at Vermilion Lock totaled 47,732 mm.

This could be due to distribution and occurrence of the synoptic weather types across the coastal zone, or it could be a manifestation of the effects of the different environments sampled. A stronger possibility, however, is that these differences in magnitude and frequency are related more to location back from the coast. The three most central locations -- Eugene Island, Luke's Landing, and Vermilion Lock -- are also the locations closest to open water. The greatest number of observations and the largest mean responses are found at these three locations, suggesting that not only do meteorologically induced changes in water level greater than 60 mm occur at those locations more often than at the other locations, but also that larger changes related to weather events occur more routinely in these more coastal areas.

One further inference from the information in the table pertains to the character of the mean responses. Since none of the mean responses in either of the surplus situations is zero, but instead are all either positive or negative, a greater influence of either those weather types that increase or those that decrease water levels is indicated at the separate locations. The range of responses to both surplus and nonsurplus conditions demonstrates the variety of impacts weather can have in forcing water level changes.

Thus far the discussion has emphasized derivation of general responses of water levels to the components of climate. A fairly well-defined picture of the responses of water levels, both regionally and at specific locations, has been developed. These established relationships were subjected to rigorous testing to identify specific areas of variation, strength, and weakness within the relationships, thereby providing a deeper understanding of the reactions of water levels regionally and in the different environments to the input of the synoptic weather types.

Statistical Evaluation of Relationships

Although each of the synoptic weather type combinations was shown to produce the anticipated response, analysis of variance (ANOV) detected that mean responses to the separate weather types were not all significantly different from each other. In addition, differences and similarities of responses at each location were analyzed collectively (not by weather type), and responses to each weather type at each of the nine locations were tested for differences. The data in these three classes were analyzed by surplus conditions and by season. The following discussion details the interpretation of the analyses in this format.

Appropriate ANOV tables are presented in the discussion; others in which results were not specifically pertinent to the discussion or were repetitive are included as an appendix. Tables of specific hypotheses, answering specific questions about each category tested, are included in the discussion of each ANOV table. In the tables of specific hypotheses, mean water level responses are ranked in order of magnitude to facilitate display and interpretation. For ease in understanding the tables it should be explained that the means connected by the same underlining exhibit no significant differences, whereas those not connected by a common underlining are significantly different. Thereby the differences within each of the categories are summarized and displayed concisely. Tukey's ω statistic, the difference between means required for significance, is also shown in each table of specific hypothesis.

Nonsurplus Conditions:

Table 4.3 shows the results of the statistical analysis of all observations during nonsurplus conditions for the three classes. The highly significant difference found among mean responses to the eight synoptic weather type combinations indicates that water levels respond to at least some of the synoptic weather types differently enough to objectively prove their existence as discreet forcing functions, different from other synoptic weather types. The significant difference found among mean responses at the nine locations indicates that water levels respond differently to meteorological input at some of the locations than at others. The highly significant difference found among the mean responses of water levels to each synoptic weather type combination at each different location indicates that the influence of some of the weather types is not the same at all of the locations.

Table 4.3

Nonsurplus ANOV

Source	d.f.	SS	MS	F
Total	1044	304.811		
Synoptic Weather Type Combination	7	70.36	10.051	58.15**
Location	8	3.07	0.383	2.22*
Combination at Location	54	16.09	0.297	1.72**
Error	975	168.53	0.172	

Synoptic Weather Type Combinations -- Specific analysis showed which weather types caused significantly different responses (Table 4.4).

Table 4.4

Differences Among Synoptic Weather Type Combinations, Nonsurplus

1	2	3	6	8	5	7	4	
-161	-62	-46	39	39	74	112	160	$\omega = 47$

Weather associated with combination 1, a cold front passage, and combination 4, a shift from northerly to easterly-southeasterly circulation, produced a response different from any other weather circumstances. Combinations 2 and 3 produced responses similar to each other, and the responses differed from any other combination. Responses to combinations 5, 6 and 8 were similar to each other but differed from the others. Combination 7 evoked a response similar to that of combination 5, but differed from all others.

Locations -- Significantly different responses indicated among locations were isolated, and all the variation was found in the responses at Eugene Island (Table 4.5).

Table 4.5

Differences Among Mean Responses
Spatially, Nonsurplus

EI	Ch	GC	Mi	Ri	Co	LL	Ha	VL	
-95	-8	-2	2	8	13	16	17	32	ω = 51

Mi = Midlake
Ch = Chevreuil
Ri = Rigaud
Co = Cocodrie
EI = Eugene Island
LL = Luke's Landing
VL = Vermilion Lock
GC = Grand Chenier
Ha = Hackberry

One explanation for the difference in response detected at Eugene Island might be that data for 1970 were used in the Eugene Island analysis, and 1971 data were used at the other stations. A more likely explanation, however, is that the Eugene Island station is the only one located in open bay waters and directly in front of the mouth of a large river system. Responses measured there are consistently larger than most other locations.

Synoptic Weather Type Combination at Each Location -- Exact sources of variation in the response of water levels to each synoptic weather combination observed at each separate location were identified (Table 4.6). Combination 1 produced statistically similar responses at Midlake, Chevreuil, and Rigaud. However, these responses were significantly smaller than responses to that weather condition at the other six locations, among which no significant differences existed.

A possible explanation for the consistently smaller responses to cold front passages at these three locations is suggested by their location on the eastern edge of the coastal region. The mean position of the polar front is much closer to these three locations; that is, fronts do not go as far beyond these three locations as they do at the others. The frequent proximity of the front immediately offshore would tend to reduce or retard responses at these eastern locations because water moving inland due to southerly circulation on the equatorial side of the front would block the expected offshore flow of water behind the front. The fact that Cocodrie, the next location to the west of these three sites, is next to these in order of magnitude of response to combination 1 supports this explanation.

Combinations 2, 3, 5, and 7 produced the same responses, statistically, at all locations, but responses to combination 4 were significantly smaller at Midlake and Chevreuil than at Luke's Landing and Vermilion Lock. Combination 6 produced a mean response at Eugene Island that was significantly smaller than at all other locations,

Table 4.6

Differences Among Mean Responses to Synoptic Weather Type Combinations at Each Location, Nonsurplus

1	VL	EI	Ha	LL	GC	Co	Ri	Mi	Ch	$\omega = 66$
	-199	-187	-178	-173	-160	-152	-82	-34	-20	
2	EI	VL	Mi	GC	Ch	Ri	LL	Co	Ha	$\omega = 162$
	-99	-91	-88	-72	-64	-57	-57	-27	-19	
3	LL	EI	Ch	Ri	Co	GC	Ha	VL	Mi	$\omega = 113$
	-97	-92	-79	-50	-43	-32	-27	-25	-10	
4	Ch	Mi	EI	Ri	Ha	Co	GC	LL	VL	$\omega = 171$
	0	53	72	91	121	126	155	207	242	
5	EI	Ri	Ch	Ha	Co	LL	GC	Mi	VL	$\omega = 188$
	6	43	67	67	69	76	76	81	105	
6	EI	Ha	GC	Mi	Ri	LL	Ch	Co	VL	$\omega = 124$
	-53	-12	10	21	35	49	61	64	96	
7	EI	Mi	Ch	Ri	Ha	GC	LL	Co	VL	$\omega = 134$
	43	52	68	74	83	123	132	145	150	
8	Co	EI	VL	LL	Mi	Ha	GC			$\omega = 236$
	-91	-8	-3	15	91	91	162			

and the large negative mean response to combination 8 at Cocodrie differed significantly from the others.

Ranking mean responses produced by each synoptic weather type combination at each location in order of magnitude reveals an important spatial aspect of water level's reaction to weather by showing the relative size of responses in the different environments across the coastal zone (Table 4.6). For example, responses at the Eugene Island location are larger in almost all weather type combinations. Moreover, since no other such consistent patterns appear, the remaining distribution of mean responses, the relative effect of each weather type and their relative magnitudes are effectively displayed.

Seasonal Appraisal -- The manner in which responses to the weather types differed through the year was assessed by analysis of responses occurring during each season in each of the three classes. Because much of the outcome was repetitive, the complete analysis is not presented in the discussion. ANOV tables and specific hypotheses tables for the analyses are included as Appendix B for detailed inspection.

Highly significant differences were found among mean seasonal responses to some of the synoptic weather type combinations. Specific weather types that caused seasonally variable responses were generally the same each season. For example, responses to combination 1 were significantly different in each season, whereas responses associated with combinations 4, 5 and 7 were essentially the same each season.

Responses to all observed weather at each location were tested to determine if the responses were different each season. Significant differences were detected among responses at the different locations only in the summer season. The variation was at Eugene Island where the mean summer season response was significantly larger than responses at Cocodrie and Midlake for that season.

Significant differences were found among seasonal mean responses induced by each synoptic weather type combination at each location only in the fall season. Combination 3 produced mean fall season responses at Luke's Landing that differed significantly from mean responses at any other location during that season. No other weather type caused any significant differences during the fall season.

Surplus Conditions:

Table 4.7 shows the results of the statistical analysis of observations during surplus conditions. Highly significant differences were detected among mean responses to each synoptic weather type combination. However, no significant differences were found among mean responses at the separate locations or among mean responses to each synoptic weather type combination at each location.

These results indicated that the influence of each weather type was essentially the same at every location during surplus conditions, or in other words, the presence of surplus negated any differences in response prompted by differences in environment. For example, the presence of surplus apparently diminished the differences in nonsurplus response detected at Eugene Island to the point of nonsig-

Table 4.7

Surplus ANOV

Source	d.f.	SS	MS	F
Total	620	248.35		
Synoptic Weather Type Combination	7	42.57	6.08	22.31**
Location	8	2.29	0.28	1.05
Synoptic Weather Type at Location	51	15.35	0.30	1.10
Error	554	151.01	0.27	

nificance. The results also suggested that the synoptic weather types were more dominant in forcing water level responses than were the additive effects of surplus.

Synoptic Weather Type Combinations -- Sources of variation creating the highly significant differences among the synoptic weather type combinations were isolated (Table 4.8). Combination 1 caused responses which were significantly different from any others. Combinations 2 and 3 had similar responses but they differed from all others. Responses to combination 4 were similar to only those of combination 7. Combinations 5, 6, 7 and 8 showed essentially the same responses, although when compared separately, responses to combination 6 were significantly different from those to combination 7.

Table 4.8

Differences Among Synoptic Weather Type Combinations, Surplus

1	2	3	6	8	5	7	4	
-175	-81	-42	39	58	79	138	173	$\omega = 77$

Seasonal Appraisal -- Highly significant differences were detected among mean responses to the synoptic weather type combinations in winter, spring, and summer seasons, and significant differences were found among these responses in the fall season. ANOV and specific hypotheses tables are included in the appendix. Because of the absence of any consistent patterns of occurrence, sources of variation in the responses as well as seasonally differing magnitude of the responses are not discussed in detail, but may be assessed easily by inspection of the tables. No significant differences among responses at the separate locations or among responses to each weather type at each location were found in any season.

Summary of Variability

Visual displays summarize pertinent information on variability of water level responses to climatic input throughout the coastal zone for both nonsurplus and surplus conditions (Fig. 4.12). Mean regional responses to each synoptic weather type combination are plotted along with departures from that mean at each location. The number of observations, the overall mean response, and the standard

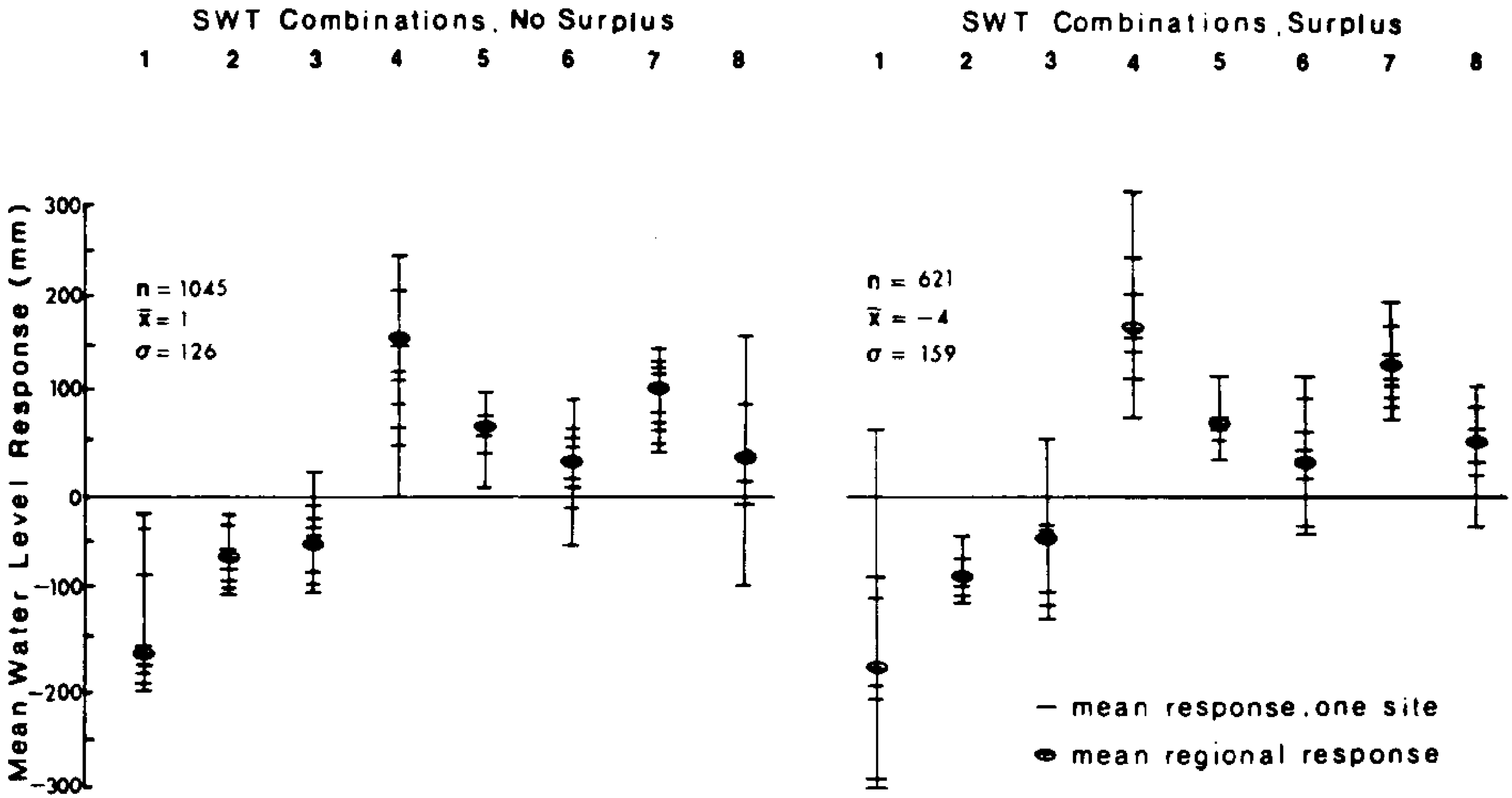

Figure 4.12: Variability of Mean Water Level Responses, Nonsurplus and Surplus Conditions, 1971

deviation for each surplus situation are shown.

This display of dispersion vividly depicts the variability and range of responses both to the different weather type combinations and at the different locations. For example, it can be seen in the figure that responses during surplus conditions (σ=159) are more variable than responses during the nonsurplus conditions (σ=126). Although the same pattern of response is evident in both surplus situations, the range of responses to each synoptic weather type combination varies considerably between nonsurplus and surplus conditions. This is especially evident in the responses to combinations 1, 3, and 8.

Table 4.9 shows the number of observations in each season, the seasonal mean water level response, and the standard deviation of each seasonal mean recorded in both nonsurplus and surplus conditions. Responses were generally larger in winter than spring, but variability of responses was about the same during those seasons. Responses in all seasons were larger and more variable when surplus was present. Fall season responses exhibited about the same variability as those in winter and spring, but variability in summer was considerably less. This reflected the less variable and less intense weather events of summer (with the exception of the GTD weather type), and indicated that weather exhibited less influence on water levels during that season.

Mean seasonal responses compared with mean annual response to each synoptic weather type combination revealed the seasons in which each weather type produced strongest and weakest responses (Fig. 4.13).

Table 4.9

Variability of Seasonal
Water Level Responses

	n	$\bar{X}$(mm)	σ
Nonsurplus			
Winter	286	12	134
Spring	354	3	138
Summer	158	-17	89
Fall	247	- 4	120
Surplus			
Winter	183	-32	183
Spring	141	- 7	183
Summer	143	23	90
Fall	154	8	158

For instance, combinations 1 and 4 produced strongest responses in winter and spring, whereas combinations 2, 3, 5, and 6 produced strongest responses in winter and spring when no surplus was present, but in fall and spring when surplus was present.

Effects of weather on water level fluctuations have been assessed spatially for the coastal zone from analyses of patterns of response determined for various environments. From these analyses, regional responses have been deduced, but they were based on data for one year (1971). How representative that year was in terms of climate must yet be considered. Moreover, in some instances, the relationships established were limited by occurrence of the particular weather types, hence some of the ratios developed to describe the caliber of the relationships were based on very few observations.

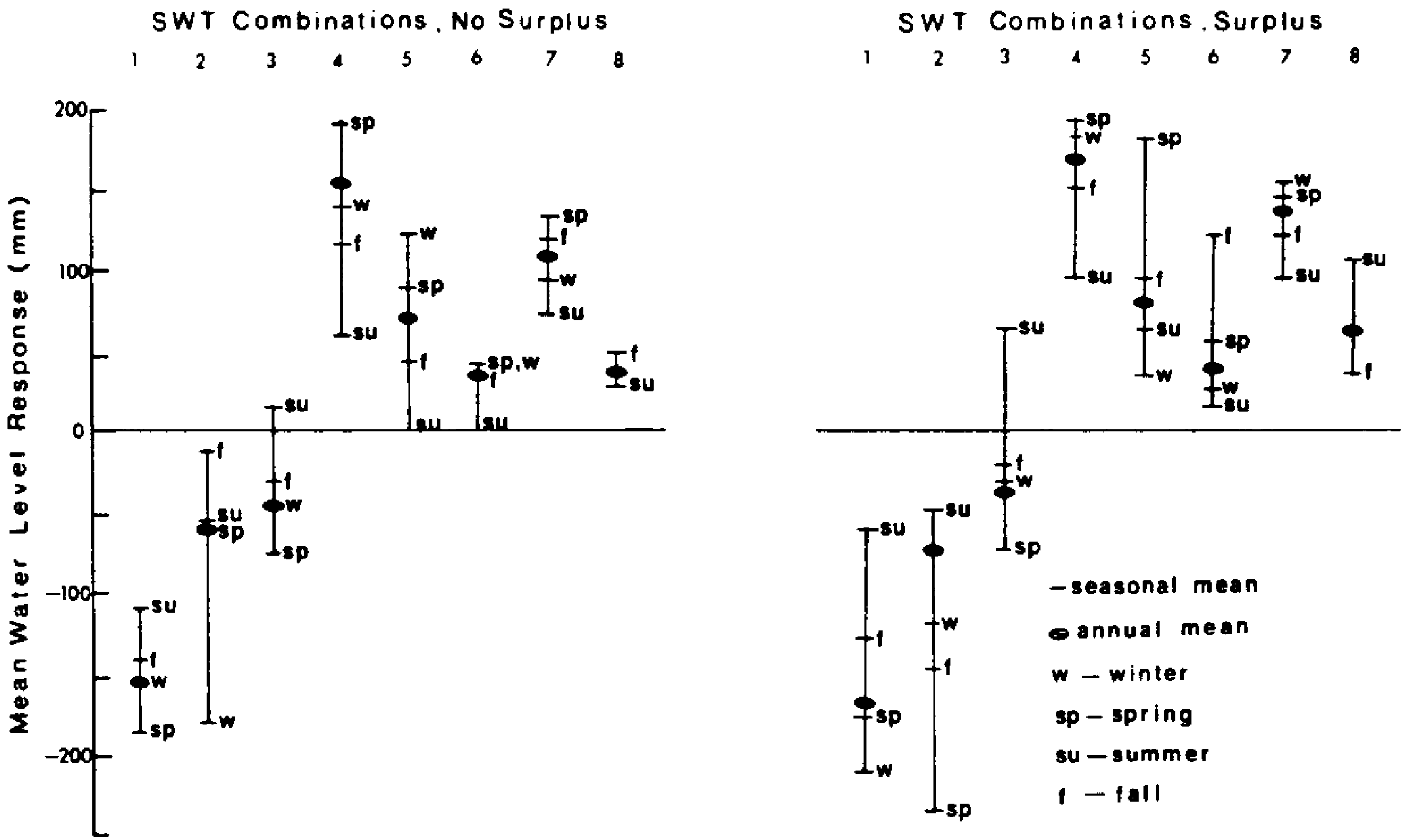

Figure 4.13: Variability of Seasonal Mean Water Level Responses, Nonsurplus and Surplus Conditions, 1971

For these reasons analysis of one of the nine locations was extended temporally to determine if the pattern of these relationships altered when a series of consecutive years was analyzed.

CHAPTER V

TEMPORAL EXTENSION OF ANALYSIS

Introduction

The specific purpose of a temporal extension of the analysis is to enlarge the sample of water level responses to each synoptic weather type combination. This temporal analysis should reinforce the existence of the anticipated relationships, providing a more representative estimate of the responses, and greater insight into the variability of the responses. A period of 10 years, 1966 through 1975, is analyzed.

The location used for the analysis, Bayou Chevreuil, was selected for a number of reasons. The water level record at this site was particularly homogeneous and intact, and the location was also close enough to the climatic baseline station at New Orleans to obviate the need for extrapolation and interpolation of the weather type calendars. Additionally, while this location showed expected responses (84%) fairly close to the mean expected responses for all locations (80%), it exhibited a smaller number of measurable responses to each synoptic weather type combination than any other location, consequently providing a more manageable number of observations over the 10 year period.

General Relationships

The result of the 10 year analysis confirmed the existence of the familiar pattern of responses (Fig. 5.1). The number of observations employed in the analysis was 663, of which 83% showed the expected response. Percent of expected responses for individual years ranged from 78 to 89%. Mean responses to each synoptic weather type combination, surplus and nonsurplus conditions, were all in the presumed direction with one exception -- combination 1 with surplus.

This deviation from the anticipated response is clearly evident in Figure 5.1. Water level responds to this weather condition with a positive mean change. The fact that this location is in an enclosed drainage basin with most of the drainage restricted to channels connecting the bayou with open lakes and marshes to the south provides adequate reason for the anomaly. Water is pushed south in the basin by a cold front and associated northerly winds, but the surplus initially causes water confined in the channels to rise instead of fall. After water south of the gauge site is moved farther down the basin, water levels begin to fall as evidenced by the response shown to combination 3, typically the weather following passage of a cold front. Some of the error found among responses to combinations 1 and 3 could also be due to rapid rises but slow drops in stage, characteristic of stream regimen, giving numerous observations greater than 60 mm on the rising stage but few on the falling stage. Byrne, et al (1976) have shown that a histogram of the Bayou Chevreuil water levels exhibits a tendency of skewness toward higher values more than any other gauge site in the Barataria Basin. This strongly suggests predominance of stream control and constricted drainage.

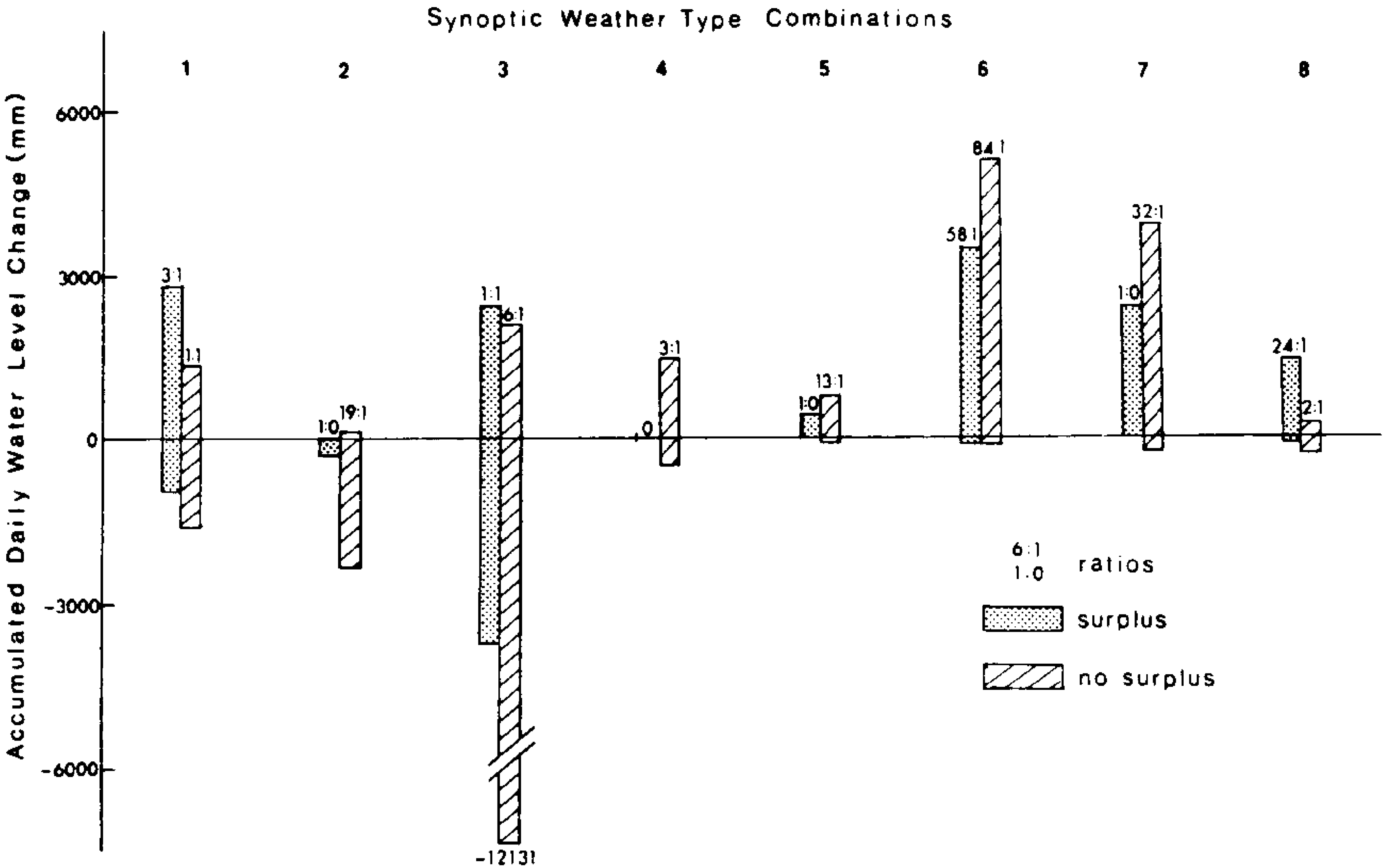

Figure 5.1: Response of Water Levels to Synoptic Weather Types, Chevreuil, 1965-1975

Identification of the effect of the availability of surplus on the responses was one of the most striking results of the temporal analysis. The prediction was that surplus water would decrease falling water levels and would augment rising water levels induced by wind directions associated with the synoptic weather types. Analysis of 1971 data at the nine locations showed the existence of this expected response most of the time, but employing 10 years of data strongly confirmed the existence of the relationships (Fig. 5.2).

As seen in the figure, water levels fell less in response to combinations 1 and 3 on occasions when surplus water was present. Responses to combination 2 with surplus did not show the expected result, but this weather condition occurred only four times in the 10 years, and this extremely small sample is very likely the reason for the anomalous result. Combination 4 did not occur with surplus, but responses to combinations 5, 6, 7, and 8 were augmented as assumed by the presence of surplus water.

Relationships established during the year 1971 (Fig. 4.5) can be compared with the relationships established in the 10 year analysis (Fig. 5.1) for an example of the variability of relationships possible when one year is analyzed separately. Eighty observations were used in the 1971 analysis, and 84% of them fit the presumed pattern. Surplus/nonsurplus relationships are not as strongly established with one year's data, but the expected relationships are proved.

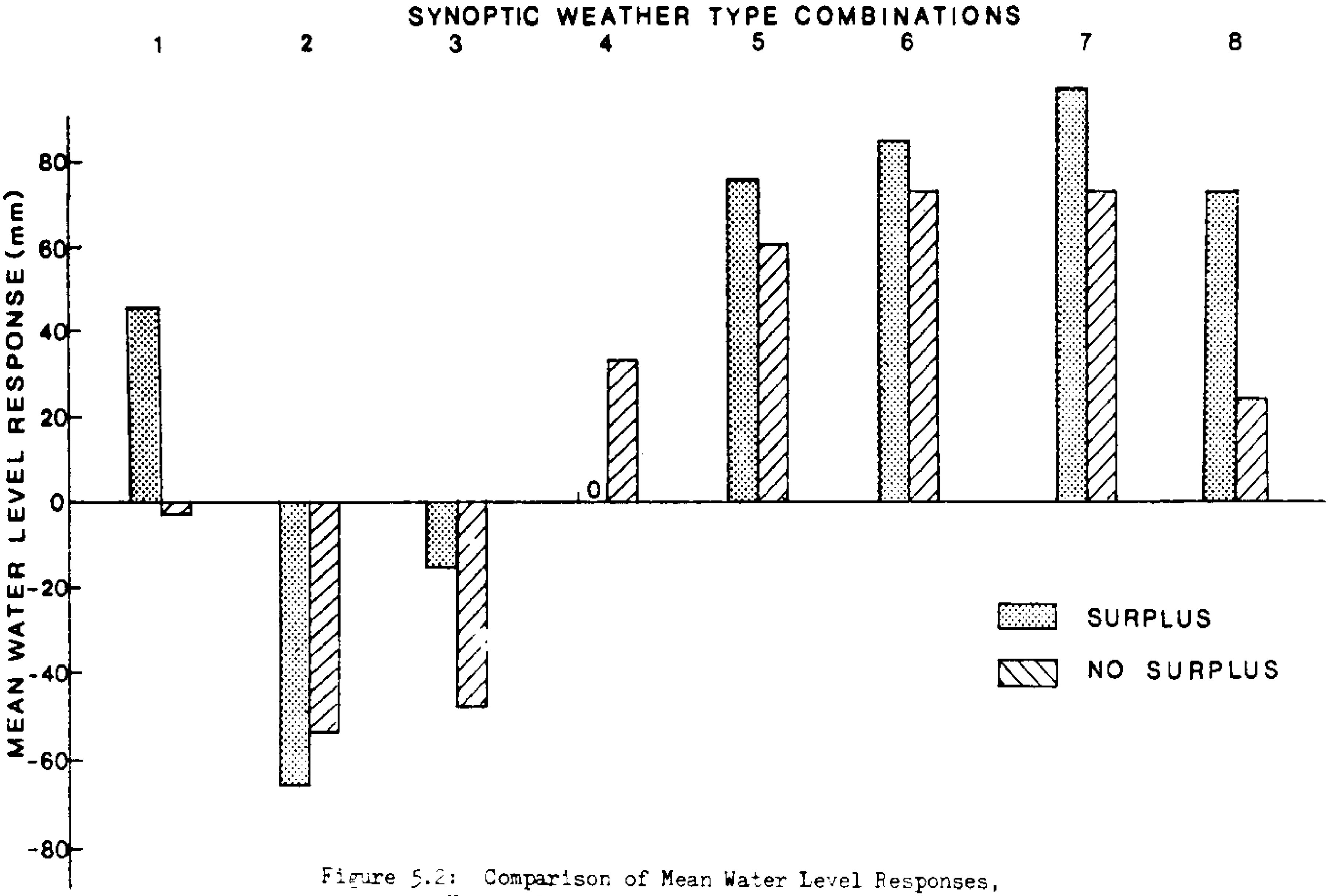

Figure 5.2: Comparison of Mean Water Level Responses,
Nonsurplus and Surplus Conditions,
Chevreuil, 1965-1975

Variability

Variability of mean responses from year to year has been assessed for each of the synoptic weather type combinations, showing the dispersion about the overall mean for nonsurplus and surplus conditions (Fig. 5.3). Occurrence of years with anomalous mean responses to the synoptic weather types as well as the difference in variability of responses between nonsurplus and surplus conditions is shown.

With the exceptions of combinations 2 and 8, responses to synoptic weather types with surplus are more variable than responses to occurrence of the weather types without surplus. Probable effect of the small sample for combination 2 has been discussed. Combination 8 with surplus would logically produce a more consistent reaction than its occurrence without surplus. The former represents the typical GTD with characteristic easterly-southerly winds and copious rainfall, whereas the latter represents early or late stages, or possibly marginal cases of the GTD synoptic weather type.

No single year exhibited consistently different responses, so no generalizations about variability among the annual mean responses are possible. However, an index of the occurrence of continental air, represented by the FOR and CH weather types, shows a distinct break in 1970 (Fig. 5.4). This may indicate some change in the placement of the longwave pattern of the westerlies, altering the frequency and duration of the synoptic weather types dependent upon the location of the polar jet stream for the frequency of their occurrence

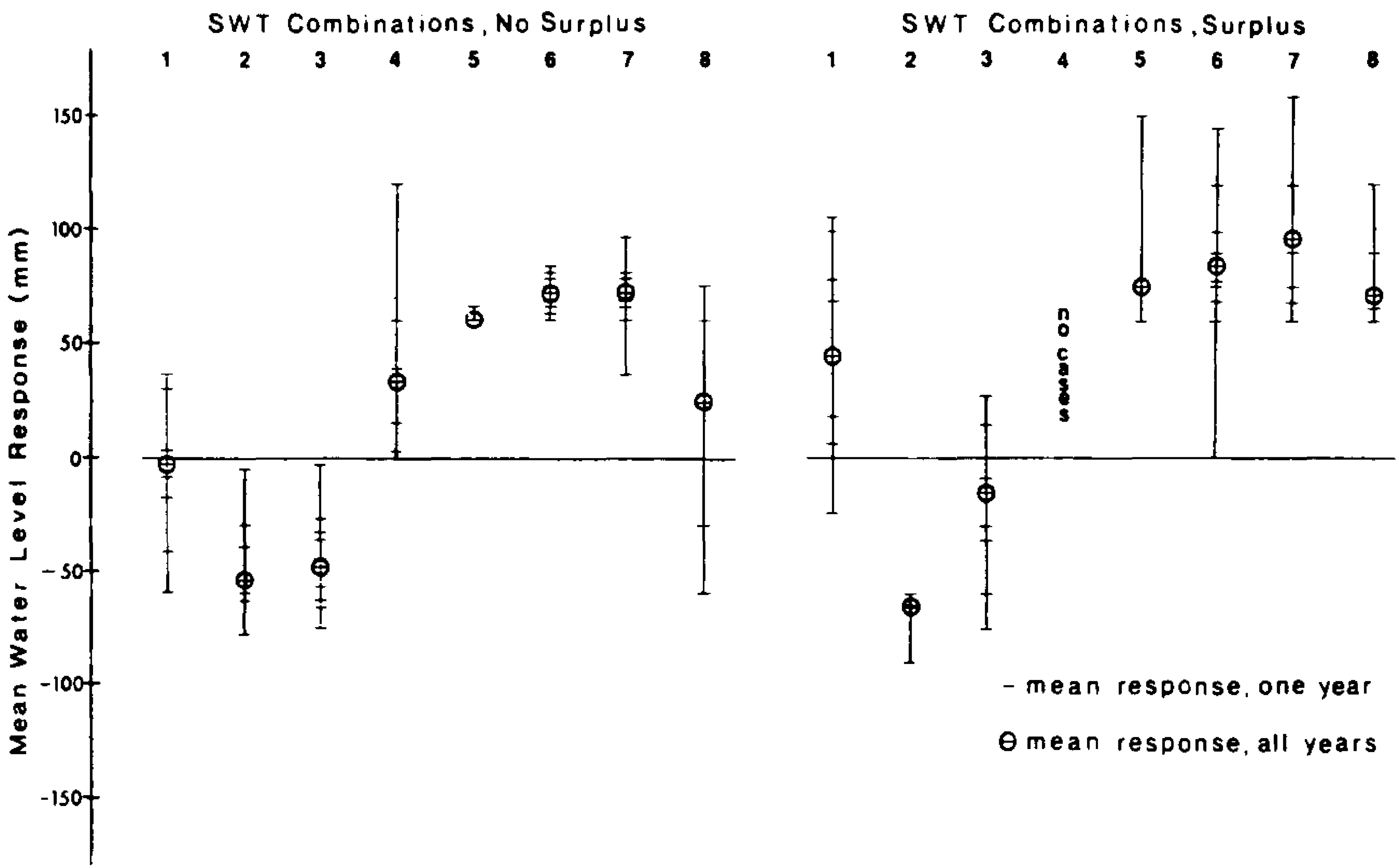

Figure 5.3: Variability of Mean Water Level Responses,
Nonsurplus and Surplus Conditions,
Chevreuil, 1965-1975

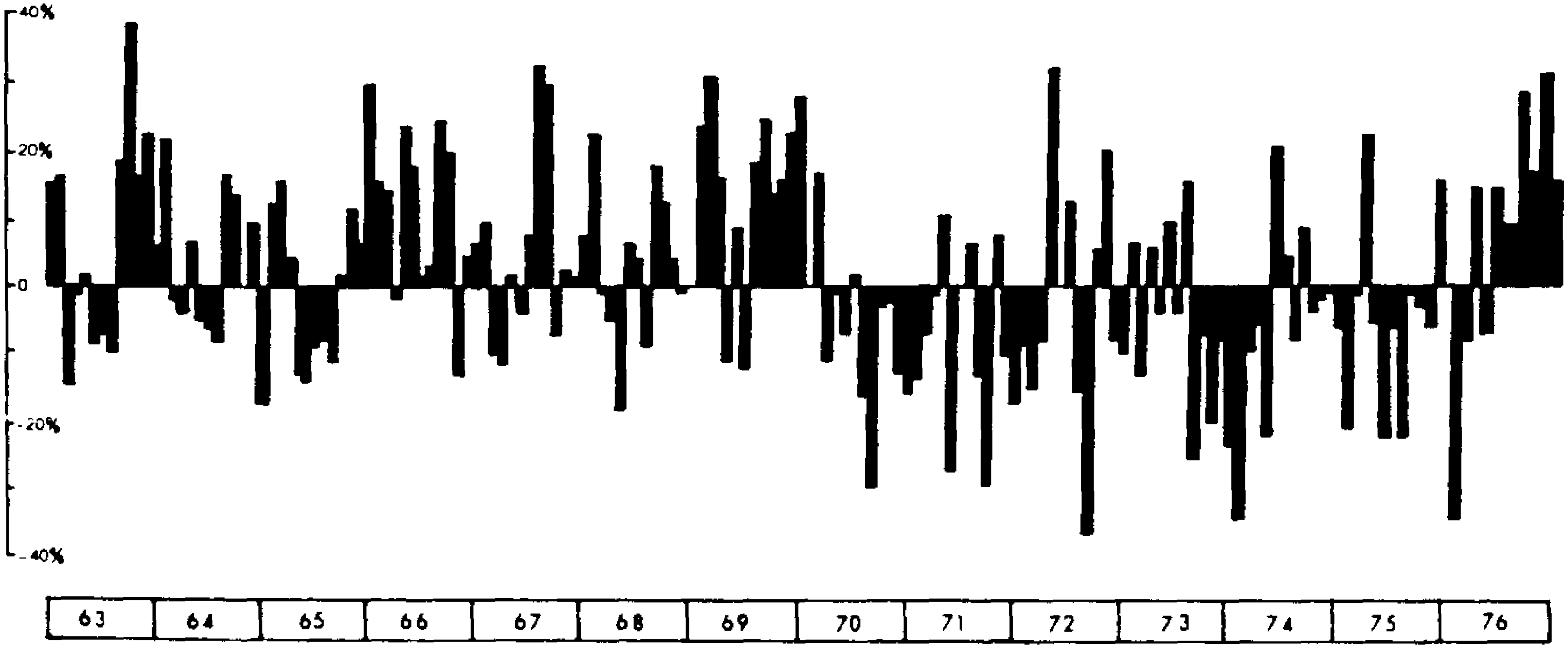

Figure 5.4: Continental Index Departures,* New Orleans
(courtesy R.A. Muller, 1977)

*Departures from 1966-1975 mean percent monthly occurrences.

in the Louisiana coastal zone (CH, FOR).

Some evidence of the environmental impact of this climatic variability is noticeable in the responses of water levels. The years 1966-69 included 150 cases of combination 3 which accounted for 48% of the total water level changes attributed to meteorological forcing during those years. The four years following the apparent change, 1971-74, had only 64 cases of combination 3, and that weather condition accounted for only 29% of the meteorologically induced water level changes during those years. This 19% difference was more than two times greater than the difference between occurrences of any other synoptic weather type during these two periods. The difference in total accumulated change in water levels produced by weather events also points out the relationship between strength of the atmospheric circulation and consequent environmental responses. The four years prior to 1970 had a total change of 23,683 mm, whereas the four year period following 1970 had a total of only 16,947 mm.

Temporal extension of the analysis enhanced the reliability of the established regional relationships, producing the same basic pattern of responses by using increased numbers of observed fluctuations in each synoptic weather type combination. Additionally, the 10-year period provided an assessment of the effects of climatic variability, confirming that the regional relationships based on 1971 data are essentially the same relationships that would have been established using observations from any of the 10 years analyzed. Thus the temporal analysis has added a valuable dimension to the regional analysis.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary of Analysis

Regional relationships between climate and water level fluctuations were established by using a synoptic weather type framework to index climatic input coupled with numerically filtered water level records to identify meteorologically caused changes in water levels. The analysis was performed using data for one year at nine locations that represent the various environments of Louisiana's coastal wetlands. Scope of the analysis was broad enough to cover environmental responses across the entire length of the coastal zone. Consequently, the analysis yielded a macro-scale insight into daily water level fluctuations resulting from forcing by climatic components. By analyzing responses in the nine sites sampled, conclusions about the regional relationships were rendered more representative.

Strengths of the relationships at each location were evaluated by computing ratios of accumulated positive change to accumulated negative change, during nonsurplus and surplus conditions, for each synoptic weather type combination. Spatial and seasonal variations of the strengths were assessed graphically and statistically. Mean responses and range of responses to each weather type at each location were determined as were the effects of the occurrence of surplus fresh water on the relationships.

It was found that water levels responded most sharply and most consistently to the changing of weather types, represented by passage of a cold front (combination 1), veering of winds from northerly to easterly or southerly (combination 4), and passage of a warm front (combination 7). Weakest relationships were found in connection with the weather types representing sustained weather -- northerly winds (combination 3) and southerly winds (combination 6) -- during which steady-state conditions were rapidly reached or approached, and decreasing effects of weather were thereafter evident. Effects of surplus fresh water on the relationships were not strongly established in the regional analyses, although the predicted effect was observed in most cases.

With the following exceptions the relationships derived from the regional analysis hold true in every location analyzed:

1) Response to passage of a cold front with surplus at Chevreuil -- representing the effects of constricted drainage and stream dominance;

2) Responses to sustained northerly flow with surplus at Eugene Island and without surplus at Hackberry -- representing probable effects of the regimes of large river systems;

3) Responses to sustained southerly flow with surplus at Cocodrie and Vermilion Lock and without surplus at Eugene Island -- the former representing an unexplained situation within the scope of this research, and the latter representing possible development of currents in Atchafalaya Bay

under the steady-state wind conditions of this weather condition; and

4) Response to Gulf tropical disturbances without surplus at Hackberry -- representing effects of western location and river basin response characteristics.

Weaker relationships were generally found in enclosed lakes or river systems with interconnecting lakes and pools that tended to pond water and thus retard or reduce responses. These surface hydrologic conditions are found at the Midlake, Grand Chenier, and Hackberry locations, and water levels at these three locations exhibited the lowest percentages of expected responses. All the bayous and other small streams responded with surprising similarity (84% expected responses at Cocodrie, Luke's Landing, and Vermilion Lock), supporting the representativeness of the analysis and the credibility of extending the results to similar environments which were not analyzed. Magnitude of response was found to be dependent upon distance from the shoreline and upon the degree to which the location represented open water.

The analysis was extended to 10 years at the Chevreuil location to provide more observations of responses to all the weather types, thus making it possible to place a greater degree of confidence in the relationships established. The pattern of responses identified was the same as that found in the regional analysis. Therefore, the reliability of the results of the regional analysis, based on one year's data, was supported. Effects of surplus water on the relationships were sharply distinguished in the temporal analysis, and as might be expected, showed that surplus water diminished falling water levels and augmented rising water levels. Furthermore, by using 10 consecutive years of data, the effect of annual climatic variability on environmental responses was touched upon briefly. No single year was found to exhibit exceptionally or consistently different responses, but an apparent change detected in atmospheric circulation during the 10-year period analyzed was related to an apparent difference in total water level fluctuation.

Although the analysis produced consistent results and substantiated them fairly well, a point of conjecture remains. Are the nine environments sampled, and the results obtained from responses observed at them, sufficiently representative to establish confidently the true process-response interactions occurring in every similar environment across the coastal zone? In other words, are the responses studied similar to those to be found in the same types of environments which were not sampled? Do the regional responses found here represent the real responses of water levels?

These questions cannot be fully answered by this research, but the repetitive character and the consistent caliber of the relationships established at each of the locations analyzed, and the results of the temporal analysis, support the correctness of the analysis. It is therefore reasonable to consider these results sufficiently representative to fulfill the objective of this research, and to assume with fair confidence that if the weather occurring in any part of the coastal zone is known, water level response to that weather is predictable.

Since the objective of this research was to establish the regional response of water levels to climatic input, anomalies in individual analyses were not thoroughly resolved. The dissimilarities were identified, located, and considered relative to their modification of the mean regional responses. Therefore, additional work remains for future research to explain in detail the particular response functions of water levels in micro-environments of the coastal zone.

Conclusions

Properties and temporal sequences of synoptic weather types, especially variations in precipitation and wind characteristics, affect water levels in the coastal zone. Occurrence of precipitation-producing weather types over the region governs production of surplus water and runoff; a direct relationship with area hydrology exists. Other environmental impacts may not be so obvious.

Patterns in the physical landscape are complex because so many natural processes interact with such varying degrees of intensity. Resulting environments are strongly related to climatic conditions, especially those in the coastal zone where processes of land, sea, and atmosphere must interact. The predictable pattern of responses to the regional climate identified in this research demonstrates the usefulness of the synoptic weather types in providing a reasonably effective method of assessing the comprehensive effects of climate on environmental responses.

It is concluded that similar techniques will be successful when used to investigate other environmental parameters. For instance, salinity conditions may correlate with the occurrence and duration of the weather types, either directly or indirectly, and are therefore suggested as a possible area of interest for future study. Evaporation and transpiration rates, periods of marsh biomass growth and activity, estuarine biological productivity and quality, and a host of other environmental responses may be related to weather conditions from many perspectives and for a number of objectives. Landform parameters such as coastal configuration and orientation of lakes and rivers may influence predicted relationships, and it is suggested that future studies employing the techniques developed in this research weigh these parameters appropriately.

The method of condensing the totality of climate into repetitive types of weather with known characteristics, and then relating the occurrence and duration of those types to environmental response, should improve our understanding of the impact of climatic elements as forcing functions for natural processes. Application of synoptic climatology to environmental studies, in which the physical input of climate must be considered, thus offers possibilities for substantially increasing and quantifying our knowledge about the intricate interactions of natural systems.

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APPENDIX A

ABBREVIATIONS AND SYMBOLS

Table A.1

Abbreviations and Synbols Used

PH	-	Pacific High
CH	-	Continental High
FOR	-	Frontal Overrunning
CR	-	Coastal Return
GR	-	Gulf Return
FGR	-	Frontal Gulf Return
GH	-	Gulf High
GTD	-	Gulf Tropical Disturbance
C.O.E.	-	U.S. Army Corps of Engineers
PE	-	Potential Evapotranspiration
NS	-	Nonsurplus
S	-	Surplus
SWT	-	Synoptic Weather Type
Mi	-	Midlake
Ch	-	Chevreuil
Ri	-	Rigaud
Co	-	Cocodrie
EI	-	Eugene Island
LL	-	Luke's Landing
VL	-	Vermilion Lock

Table A.1 (cont'd.)

GC	-	Grand Chenier
Ha	-	Hackberry
ANOV	-	Analysis of Variance
ω	-	Tukey's Statistic
*	-	Significant statistically
**	-	Highly significant statistically
d.f.	-	Degrees of Freedom
SS	-	Sums of squares
MS	-	Mean Square
σ	-	Standard Deviation
n	-	Sample Size
$\bar{x}$	-	Mean

APPENDIX B

SEASONAL ANALYSES TABLES

Table B.1

Winter Season ANOV, Nonsurplus

Source	d.f.	SS	MS	F
Total	285	87.52		
Combination	6	20.21	3.36	7.27**
Location	8	2.11	0.26	1.36
Combination at Location	44	5.99	0.13	0.70
Error	227	44.26	0.19	

Table B.2

Differences Among Synoptic Weather Type Combinations, Winter Season, Nonsurplus

2	1	3	6	7	5	4	ω=88
-186	-159	-46	45	97	126	143	

Table B.3

Spring Season ANOV, Nonsurplus

Source	d.f.	SS	MS	F
Total	353	137.05		
Combination	6	26.19	4.36	21.15**
Location	8	0.53	0.06	0.32
Combination at Location	45	10.24	0.22	1.10
Error	294	60.67	0.20	

Table B.4

Differences Among Synoptic Weather Type Combinations, Spring Season, Nonsurplus

1	3	2	6	5	7	4	ω=81
-189	-79	-61	45	94	134	196	

Table B.5

Summer Season ANOV, Nonsurplus

Source	d.f.	SS	MS	F
Total	157	19.28		
Combination	7	3.89	0.55	6.51**
Location	8	1.50	0.18	2.20*
Combination at Location	27	1.90	0.07	0.83
Error	115	9.84	0.08	

Table B.6

Differences Among Synoptic Weather Type Combinations, Summer Season, Nonsurplus

1	2	5	6	3	8	4	7	ω=87
-113	-59	0	1	18	30	61	77	

Table B.7

Differences Among Mean Responses Spatially, Summer Season, Nonsurplus

EI	Ri	VL	Ch	GC	LL	Ha	Co	Mi	ω=95
-80	-30	-25	-20	-14	-8	13	25	39	

Table B.8

Fall Season ANOV, Nonsurplus

Source	d.f.	SS	MS	F
Total	246	59.88		
Combination	7	11.05	1.57	10.16**
Location	8	1.61	.20	1.29
Combination at Location	43	10.73	.24	1.61*
Error	188	29.23	.15	

Table B.9

Differences Among Synoptic Weather Type Combinations, Fall Season, Nonsurplus

1	3	2	6	5	8	4	7	ω=94
-140	-32	-14	42	48	50	120	120	

Table B.10

Differences Among Mean Responses to Synoptic Weather Type Combinations at Each Station, Fall Season, Nonsurplus

Combination/Station and Mean Response										
	VL	EI	Ha	GC	Co	Mi	Ri	LL		
1	-218	-204	-183	-168	-84	-81	-61	-36		ω=218
	Ha	Mi	Ch	Ri	Co	LL	GC	VL		
2	-99	-99	-61	-61	-61	-61	-9	24		ω=308
	LL	EI	Ri	Ch	Co	Mi	GC	VL	Ha	
3	-128	-86	-71	-61	-47	-27	10	46	72	ω=182
	EI	Ha	Co	GC	VL	LL				
4	-46	0	99	122	160	219				ω=284
	EI	GC	Ri	Ha	VL	LL	Ch	Co	Mi	
5	-91	30	38	42	46	48	61	73	85	ω=243
	EI	Ha	Co	LL	VL					
6	-76	30	61	107	152					ω=372
	Mi	Ch	GC	Ri	LL	Co	VL			
7	10	61	68	71	162	183	284			ω=309
	Co	Mi								
8	-91	61								ω=336

Table B.11

Winter Season ANOV, Surplus

Source	d.f.	SS	MS	F
Total	285	87.52		
Combination	6	20.21	3.36	7.27**
Location	8	2.11	0.26	1.36
Combination at Location	44	5.99	0.13	0.70
Error	227	44.26	0.19	

Table B.12

Differences Among Synoptic Weather Type Combinations,
Winter Season, Surplus

1	2	3	6	5	7	4	ω=151
-219	-125	-39	26	35	157	188	

Table B.13

Spring Season ANOV, Surplus

Source	d.f.	SS	MS	F
Total	140	36.68		
Combination	6	15.10	2.51	6.93**
Location	8	5.73	0.71	1.97
Combination at Location	25	9.10	0.36	1.00
Error	101	43.21	0.42	

Table B.14

Differences Among Synoptic Weather Type Combinations, Spring Season, Surplus

2	1	3	6	7	5	4	
-244	-182	-79	55	148	183	197	ω=173

Table B.15

Summer Season ANOV, Surplus

Source	d.f.	SS	MS	F
Total	142	17.40		
Combination	7	2.87	0.41	4.67**
Location	8	0.73	0.09	1.05
Combination at Location	28	1.85	0.06	0.75
Error	99	8.69	0.08	

Table B.16

Differences Among Synoptic Weather Type Combinations, Summer Season, Surplus

1	2	6	5	3	7	4	8	
-64	-53	18	61	66	96	96	108	ω=93

Table B.17

Fall Season ANOV, Surplus

Source	d.f.	SS	MS	F
Total	153	46.48		
Combination	7	4.83	0.69	2.57*
Location	8	1.57	0.19	0.73
Combination at Location	27	3.19	0.11	0.44
Error	111	29.78	0.26	

Table B.18

Differences Among Synoptic Weather Type Combinations, Fall Season, Surplus

2	1	3	8	5	6	7	4	
-152	-135	-27	34	96	122	122	152	157

VITA

Charles Larry Wax was born in Oktibbeha County, Mississippi, on December 10, 1946, to John and Lorene Wax. He graduated from Greenwood High School in Greenwood, Mississippi, with Honors in 1965; from Mississippi Delta Junior College in Moorhead, Mississippi, with Highest Honors and with an Associate in Arts degree in 1967; and from Delta State University in Cleveland, Mississippi, as a Faculty Scholar and with a Bachelor of Arts degree in 1969.

He joined the United States Marine Corps in April, 1969, and served until December, 1972, attaining the rank of Captain. He married Nancy Elizabeth Holland in Columbus, Mississippi, in June, 1970. They moved to Baton Rouge, Louisiana, in January, 1973, where Charles entered graduate school in physical geography. Their son, David, was born in July, 1974, and Charles received his Master of Science degree in December of that year.

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